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Joint Coordinating Forum for the International Advanced Robotics Programme

First International Workshop on Robotic Applications in Medical and Health Care

Ottawa Ontario, Canada
June 23 - 24, 1988

Canada

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First International Workshop on Robotic Applications in Medical and Health Care

Within the IARP, described in the following section, the designated lead country for Medical and Health Care interests is the United Kingdom (U.K.). Canada is the main co-sponsor for the first workshop on this topic. Other IARP countries collaborating as co-sponsors are France, Germany and the United States of America (U.S.A.).

Scope of the Workshop on Robotic Applications in Medical and Health Care

The Workshop has emphasized presentations on novel research projects and results to date in a fashion fitting the purpose of a workshop. In view of the early nature of this developing technology, the organizers have been keen to offer researchers an opportunity to describe their work. Papers are therefore included which describe projects in progress as well as those describing completed work, since the intent of a workshop is to provide an informal forum for the benefit of the participants and to encourage international collaboration. By agreement, the working language of the IARP activities and workshops is English.

Topics under the general heading of Robotic Applications for Medical and Health Care include:

- Rehabilitation
- Patient care, including lifting, feeding and home care
- Autonomous vehicles and robot aids for the disabled
- Physiotherapy
- Prosthetic devices for the handicapped
- Microsurgery and therapeutic treatment
- Advanced manufacturing of pharmaceuticals and health care products
- Other related areas

It should be noted that while the submission of manuscripts by the participants was optional, we are pleased, on behalf of the participants and the programme committee, to be able to offer these proceedings as a record of the workshop and the subject matter.

Programme Committee

Prof. S.C. Lillicrap	Bath Institute of Medical Engineering	U.K.
T. Jones	UMI Systems Ltd.	U.K.
R. Egginton	Dept. of Trade & Industry	U.K.
J. Scrimgeour	National Research Council	Canada
Prof. P. Rabischong	INSERM	France
T. Martin	Kernforschungszentrum	Germany
N. Caplan	National Science Foundation	U.S.A.

R. Egginton
J. Scrimgeour
Co-Editors

Premier atelier international sur les applications de la robotique dans les domaines de la médecine et des soins de santé

À l'intérieur du International Advanced Robotics Programme (IARP), le pays directeur désigné pour représenter les intérêts en matière de soins médicaux et de santé est le Royaume-Uni (R.-U.). Le Canada est le principal promoteur du premier atelier portant sur ce sujet. Les autres pays participant au PIRA qui coparrainent cet atelier sont la France, l'Allemagne et les États-Unis d'Amérique (U.S.A.)

Portée de l'atelier sur les applications de la robotique dans les domaines de la médecine et des soins de santé

Cet atelier met en lumière les présentations portant sur des projets de recherche novateurs et sur les résultats obtenus à ce jour d'une manière qui concorde avec le but de l'atelier. Étant donné qu'il s'agit-là d'une technologie émergente, les organisateurs ont tenu absolument à donner l'occasion aux chercheurs de décrire leurs travaux. C'est pourquoi les communications présentées décrivent des projets en cours ainsi que des projets menés à bien, l'objectif de l'atelier étant de fournir une tribune libre dans l'intérêt des participants et d'encourager la collaboration internationale. D'un commun accord, la langue de travail de l'atelier et des activités du IARP est l'anglais.

Les sujets abordés sous le thème général des "Applications de la robotique dans les domaines de la médecine et des soins de santé" comprennent::

- la réadaptation
- les soins aux malades, y compris les soulever et les nourrir et les soins à domicile
- véhicules autonomes et aides robotiques pour les handicapés
- la physiothérapie
- dispositifs prothétiques pour les handicapés
- microchirurgie et traitement thérapeutique
- fabrication avancée de produits pharmaceutiques et de soins de santé
- autres sujets connexes

Il convient de noter que la soumission de manuscrits complets par les participants était facultative. Étant donné ce fait, nous sommes heureux de pouvoir vous offrir, au nom des participants et du Comité du programme, ce compte rendu que se veut un rapport officiel de l'atelier et des sujets abordés.

Comité du programme

Prof. S.C. Lillicrap	Bath Institute of Medical Engineering	R.-U.
T. Jones	UMI Systems Ltd.	R.-U.
R. Egginton	Dept. of Trade & Industry	R-.U.
J. Scrimgeour	Conseil national de recherches	Canada
Prof. P. Rabischong	INSERM	France
T. Martin	Kernforschungszentrum	Allemagne
N. Caplan	National Science Foundation	É.-U.

R. Egginton
J. Scrimgeour
Corédacteurs

International Advanced Robotics Programme — IARP

Background

At the Versailles Economic Summit in June 1982, it was agreed that further international scientific and technological cooperation would be required for the revitalization and growth of the world economy, and 18 projects, including the "advanced robotics" project, were initiated. Progress reports on these projects were made at subsequent Economic Summits, and a final report at the summit level was submitted at the Tokyo Economic Summit in May 1986,

The continued pursuit of the "advanced robotics" project as the "International advanced robotics program" was unanimously approved by all countries attending the 5th JCF (on April 3-4, 1986, in Hawaii), in keeping with the original intent of the Economic Summit.

Objectives

The objective of the programme is to encourage development of advanced robotic systems that can dispense with human work for difficult activities in harsh, demanding or dangerous environments, and to contribute to the revitalisation and growth of the world economy.

Activities

Activities of the programme include:

(1) Descriptive reports on the state of robotics R&D in participating countries

(2) Holding of workshops

(3) Exchange of study missions

(4) Exchange of researchers

(5) Implementation of joint site studies

Area of the International Cooperation

(Application Fields)

(1) Nuclear Power, (2) Underwater Operations, (3) Fire Fighting and Rescue Operations, (4) Agriculture, (5) Mining and Tunnelling, (6) Civil Engineering, (7) Plant Operations, (8) Domestic and Service, (9) Space, (10) Medical and Health Care

(Elemental Technologies)

(1) System Architecture, (2) Intelligence, (3) Sensors, (4) Man-Machine Systems and Manipulation, (5) Locomotion, (6) Actuators

Contacts for Inquiries

Canada	N. Burtnyk	National Research Council Building M-50, Montreal, Road, Ottawa K1A 0R8
France	G. Giralt	CNRS-LAAS 7, avenue du Colonel Roche, 31077 Toulous
Germany	T. Martin	Kernforschungszentrum Karlsruhe Projekttrager Fertigungstechnik Postfach 3640, D-7500 Karlsruhe
Italy	F. Barabashi	ANSALDO. S. P. A. Piazza Carignano 2,16128 GENOA
Japan	Y. Okada	Office of the National R and D Programs Agency of Industrial Science and Technology (AIST), MITI 1-3-1, Kasumigaseki, Chiyoda-ku, Tokyo
UK	R. Egginton	Department of Trade and Industry Ashdown House 123, Victoria Street, London SWIE 6RB
USA	N. Caplan	NSF 1800 G Street N.W. Washington DC 20550
Austria	H. Weseslindtner	Technische Universitat Wien 1040 Wien Karlsplatz 13
EC	J.L. Quement	Commission of the European Communities 200 rue de la Loi B-1049 Brussels
Norway	J. Ulleland	Federation of Norwegian Engineering industres (MUL) P.B. 7072 Homansbyen 0306, Oslo 3
Netherlands		

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JOINT COORDINATING FORUM FOR THE
INTERNATIONAL ADVANCED ROBOTICS PROGRAMME

FIRST INTERNATIONAL WORKSHOP ON ROBOTIC
APPLICATIONS IN MEDICAL AND HEALTH CARE

Acknowledgements

The workshop organizers wish to express their appreciation to Mrs. H. Lacoste and the staff of NRC Conferences for their able assistance in the organization of the workshop and the proceedings.

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MANUSCRIPTS

ASSESSING THE IMPACT OF ROBOTIC DEVICES FOR THE SEVERELY PHYSICALLY DISABLED

H.F. Machiel Van der Loos, EDME[†*]
Stefan J. Michalowski, Ph.D.[†*]
Joy Hammel, O.T.R.[†]
Larry J. Leifer, Ph.D.[†*]
Henk G. Stassen, Ph.D., Visiting Professor[*]

† Rehabilitation R&D Center
VA Medical Center (153)
3801 Miranda Ave
Palo Alto, CA 94304

* Design Division
Dept. of Mechanical Engineering
Stanford University
Stanford, CA 94305-3030

SUMMARY

The Veterans Administration Rehabilitation Robotics research group in Palo Alto has consistently stressed the need to maintain close links to the disabled community, particularly the spinal cord injured, to ensure that the technology developed is focused not only on the perceived, but more relevantly, on the expressed needs of the targeted users. A previously unexplored body of data, a series of questionnaires on the capability of disabled veterans to accomplish activities of daily living, is discussed. Several extensions to the basic list, both in length to accommodate vocational activities, as well as in breadth, to be able to analyze the effect of Robotic Technology on the functional independence of disabled people, are explained.

INTRODUCTION

Worldwide, there are more than a dozen research groups in the field of Rehabilitation Robotics. Each group has its own perspective on how to advance the state of the art most effectively. Some projects emphasize technology development while others concentrate on applications programming or clinical trials. This healthy mix brings up the question: Is there a common basis for assessing the value of Rehabilitation Robotics, not only in terms of dollars, but also in terms of the benefit to the end users? Based on our study which might be termed, "A day in the life of a quadriplegic," the answer is "Yes."

GOAL STATEMENT

A major goal of the Veterans Administration (VA) research program in Rehabilitation Robotics is to enhance the quality of life of disabled and infirm veterans by applying the best and most appropriate technology. The most significant impact on the quality of life of disabled individuals is the increase in personal privacy and functional independence in accomplishing daily tasks. In our research and development, we are stressing two major application areas: activities of daily living (ADL), including recreation, and vocational activities. Advances in these areas are key in defining the success of robotic assistants as viable and relevant devices for the disabled.

JUSTIFICATION

Given that there are about 60,000 quadriplegics in the U.S. today, and that each year the VA treats about 2000 new spinal cord injury patients, with an average age of less than 30 and an essentially normal life expectancy, there is a serious mandate to provide this population with the means to re-establish themselves in their own social structures. Severe physical disability results in a high level of dependence on the services of an attendant for virtually all of a person's daily and vocational needs. Based on observations and interactions with patients at the Palo Alto VA Spinal Cord Injury Center, we find that this impacts the quality of life in the following ways:

- In the U.S., quadriplegics often experience a loss of control over their lives because the details of when and how tasks are to be performed are controlled by the preferences, skills and personalities of their attendants.
- Low wages and the lack of uniform training standards often result in poor job performance by attendants. Many instances of management problems and personal conflicts have been recorded by our staff. For example, individuals sometimes spend the entire day in bed because an attendant did not arrive.
- Attendant turnover rates are high, resulting in the frequent need for disabled persons to interview prospective candidates and train new attendants to their personal requirements.
- As they become more dependent on their attendants, disabled persons may lose skills they acquired during occupational therapy at a rehabilitation clinic.

Our work occurs in parallel with other research, some funded by the VA, to develop alternate rehabilitation strategies and to study different aspects of physical disability. The training of animals such as dogs and monkeys, the application of FES, nerve-regeneration and nerve-grafting are areas of active research. Within this spectrum, robotics technology represents a viable, partial, and near-term solution to enhancing personal independence for the severely physically impaired.

BACKGROUND

The VA/Stanford Robotics Group began in 1980 with a feasibility study of a desktop voice-controlled robot. Currently, the project is concentrating in two areas: clinical and vocational assessment of a third-generation desktop system, and technology development of an omnidirectional mobile robot. Both evolutionary paths [Leifer 82] are supplemented by the study and development of language-based tools (speech recognition and voice feedback) for the human-machine interaction.

Clinical Testing of the Desktop Assistant Robot

The Desktop Vocational Assistant Robot (DeVAR) has evolved from a series of prototypes to the pre-production state (Figure 1). For the past year we have been evaluating the system's performance in the clinic with activities of daily living (ADL) such as preparing a meal and brushing teeth, and personal clerical tasks. In parallel, we are preparing a second system for off-site testing in a vocational setting. This system will contain the same robotic components [Lees 88], but will concentrate on meeting the vocational needs of a disabled programmer. We are targeting tasks such as printer-output management, textbook and manual handling, mail manipulation, as well as required workplace ADL tasks such as providing a glass of water, handling medication, feeding snacks, and personal facial hygiene (e.g., wiping the person's brow, brushing teeth).

Desktop Robot Evaluation

The clinical testing phase of the desktop system consists of training quadriplegics who are undergoing rehabilitation in the Palo Alto VA's Spinal Cord Injury Center to use the DeVAR in performing a number of ADL tasks. The one-hour training session includes pre- and post-questionnaires to assess user expectations of and reactions to the technology. The questionnaire consists of 34 questions about the person's perception of the machine's attributes, e.g., safety, strength, ease of learning, value and reliability. Twenty-three male quadriplegics have been trained in the past year. Results from the questionnaire [Hammel 88] indicate overall positive reactions to the technology. The slight evidence of skepticism in the pre-test disappeared in the post-test.

Another valuable data source is the users' actual task performance. This is available as computerized history lists of their commands to the robot. This facility is available on both the desktop and mobile systems. We are able to inspect the design of command vocabularies, the effectiveness of the status displays (including prompts and help messages), and the system's error recovery capabilities. These data files on recent training sessions have not yet been analyzed.

Figure 1. Desktop Robot System with PUMA-260 Robot Arm.
The robot arm, a Westinghouse/Unimation PUMA-260, is shown mounted upside-down on a one-meter rail, suspended above the work space. The arm can reach the table-top and can offer objects to the user. It can open and reach into the side cabinets. Notice the Otto-Bock "Greiffer" end-effector.

Technical Development of the Mobile Assistant Robot

For the development phase of the Mobile Vocational Assistant Robot (MoVAR) [Van der Loos 86], we have defined a set of sensor subsystems that will give the mobile manipulator the necessary autonomy and safety while operating under the supervisory control of a disabled user [Leifer 86; Michalowski 87a]. The choice of these elements is determined in terms of operator workload, mechanical reliability, and frequency of need in typical task situations. Based on several earlier designs, a new operator console is being prepared to allow maximal adjustability and functionality to the disabled user. This system is being prepared for clinical trials at the VA Spinal Cord Injury Center at the same time as the DeVAR is moving to its off-site testing location.

The robotic devices we are developing contain speech recognition and voice synthesis units for the primary communication link between the user and the robot's controller. An interface program presents status information on monitor screens and sends the spoken commands to the robot. Task programming is closely tied to the user's needs and to the system's geometry, grippers and sensor systems. In this regard, a desktop system has very different requirements than a mobile unit . The desktop (Figure 1 depicts the vocational workstation design) is more likely to be a well organized environment, with minimal day-to-day variability. For a 150 kg mobile robot (Figure 2) in an office or home environment, random events are more likely to become potential dangers. Chairs that have been moved, as well as the presence and movement of children, pets and toys, constitute real safety, reliability, and performance issues for mobile robots. Sensor systems [Park 87], real-time software [Michalowski 87b], and the software and hardware constituting the human-machine interface assume a critical importance. Figure 3 depicts the console of the MoVAR system. In choosing which robot systems and sub-systems offer the most performance for the investment, we must consider R&D costs, manufacturing costs, reliability, and, most importantly, relevance to users' needs.

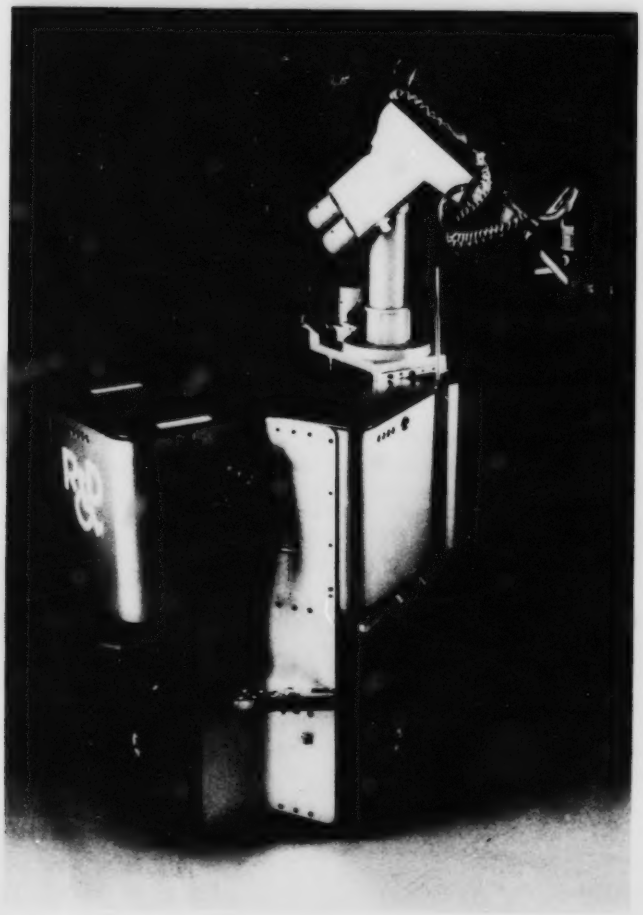

Figure 2. Omnidirectional Mobile System (MoVAR) with PUMA-260 Robot Arm.
The system is shown with its instrumented bumper, TV-camera and antenna, gripper with optical proximity sensors, and 6-axis wrist force sensor. Not visible are the on-board status console and the laser scanner. The motorized wheels with passive rollers around their circumference give the vehicle omnidirectional motion. This vehicle is capable of speeds to 6 kph, and has a 2-hour operating time between charges.

Figure 3. Operator Console of the MoVAR Robot System.
The operator of the MoVAR robot uses a headset-microphone to communicate with the IBM-PC/AT through the Kurzweil speech recognition system. He views a map of the environment on one screen, consults status information on another, and has an image from the robot's on-board camera on a third. To move the screen cursor, he uses an ultrasonic "joystick" consisting of two desk-mounted transducers, which measure head movements. The console has recessed display screens to give the user a clear view of the robot's actions.

METHODS

In order to assess the influence of robotic devices in enhancing a user's independence, we began with an Independence Rating questionnaire administered by Occupational Therapists (OTRs) to all patients in the Palo Alto VA Spinal Cord Injury Center. It is a 128-item list spanning ten categories; each patient is assigned a 1-to-7 independence score for each item. From this classification, we have identified three functional levels of independence:

D: Dependent. The person requires the assistance of an attendant, nurse or occupational therapist to perform more than 50% of a task, like putting on socks or operating an environmental control unit.

S: Semi-dependent. An attendant is needed for certain phases of the task, but typically only for set-up and stand-by. For example, for a C6 quadriplegic with limited hand motion, a wrist cuff might need to be attached so that he can use a spoon to eat a bowl of soup.

I: Independent. There is no intervention needed for the task. For example, operating an environmental control unit with a mouthstick (which is assumed to be within reach) would be rated in this category because, aside from mechanical fixtures, no one is required to assist in the task.

In addition to this rating, we have developed a Robot Enhancement Factor (REF), which measures the user's potential progression from D to S (REF = 1), D to I (REF = 2), or S to I (REF = 1), depending on the task and the person's own functional level. The resulting code therefore represents the overall functional independence level of the person with the robot. No correction was made for the increase or decrease in task-completion time in comparing an attendant with a robot. At best, this would be difficult, given the nature of attendants and robots: an attendant might be able to do a task in 30 seconds, but take 30 minutes to respond to the request, whereas a robot might take 5 minutes for the same task, but it would be instantly available, with the user in control of the process. Of course, there are a number of tasks, like a transfer from bed to wheelchair, for which no robot has yet been developed and for which the REF = 0. In such cases, the rating remains unchanged (D to D, S to S, I to I), even if the robot happens to be present.

We have tabulated data on 74 high-level quadriplegics, treated at the Palo Alto VA Spinal Cord Injury Center from 1979 to the present; the full analysis of the data is in progress. A sample of several users' profiles, taken from the "Communication" category, along with the REF-codes for all three initial disability levels, appear in Table 1.

To complement the task classification and REF tools, we have made daily logs of the activities of three quadriplegics. By combining these with each person's 128-item list compiled by the rehabilitation clinic therapist, we can graph the resulting independence level of a person for a typical day. With the REF-list, a graph of daily activities aided by a robotic device can give an accurate picture of the effect of technology on the life of a disabled person. One example is discussed in the next section.

	Patient ID	0791				9761				4120				Robot Enhancement Factor		
	Date of Birth	1/1/38				2/23/26				4/8/58						
	Date of Injury	10/4/79				10/16/82				3/9/80						
	Level of Injury	C5,6				C6,7				C5						
	Cause of Injury	Mot. Vehicle				Mot. Vehicle				Diving						
	Post-Injury Assessment (D1)	12/7/79				12/17/82				4/18/80						
	Assessment on Release (D2)	12/20/79				3/18/83				8/18/80				INITIAL STATES:		
	Most Recent Assessment (D3)	4/18/80				10/4/84				4/15/86				D	S	I
#	COMMUNICATION SKILLS		D1	D2	D3		D1	D2	D3		D1	D2	D3			
1	Write w/wo Device		D	D	D	with	D	S	S	with	D	D	S	0	0	0
2	Type w Elec/Manual-w/wo Device	with	D	D	D		D	S	S	with	D	S	S	2	1	0
3	Put Letter In Envelope	with	D	D	D		D	D	I		D	I	I	2	1	0
4	Seal Envelope		D	D	D		D	D	I		D	I	I	1	1	0
5	Open Envelope		D	D	D		D	D	I		D	I	I	2	1	0
6	Remove Letter From Envelope		D	D	D		D	D	I		D	I	I	1	1	0
7	Answer Phone-Standard/Adapted		D	D	D	standard	D	S	S	adapted	D	S	S	2	1	0
8	Dial Telephone w/wo Device	adapted	D	D	D	with	D	S	S	with	D	S	S	2	1	0
9	Handle Money For Pay Telephone	with	D	D	D		D	D	D		D	D	D	2	1	0
10	Dial Pay Phone-Booth/No Booth		D	D	D		D	D	D		D	S	S	2	1	0
11	Turn Pages w/wo Device		S	S	S		D	I	I	with	S	S	S	2	1	0
12	Operate TV w/wo env. ctrl unit	u-cuff	S	S	S	ecu	S	S	S	ecu	S	S	S	2	1	0

Table 1. Excerpt from the ADL questionnaire of the VA Spinal Cord Injury Center.
The table shows the 12 items comprising the Communications category. D1 is the 1st post-trauma assessment; D2 is the assessment just prior to the person's release from the Spinal Cord Injury Center; D3 is an assessment within several years of the person's life outside the clinic. D=dependent; S=semi-independent; I=independent. The last three columns refer to the Robot Enhancement Factor (REF), and determine, for each item, the final functional independence level we expect a quadriplegic will attain with a mobile robot system. For example, for "Sealing an Envelope", patient 0791, who was scored "D" by the therapist, would jump one level, to "S," with a robot, while patient 9761, scored "I" in his third assessment, would remain at "I."

RESULTS

To assess the value of a robotic device, a log of the activities of a C3 quadriplegic (R.Y.) was made during a typical day, starting at home at 6AM and progressing through breakfast, commute, a day at the office with his computer, and returning home. He is accompanied by an attendant 24 hours a day at present. For each item in the log, a functional rating was assigned (D, S, I), along with the elapsed time for the specific task. While many items coincided with the existing 128-item ADL list, a number relating to R.Y.'s vocational activities did not. From our experience with our desktop and mobile robot systems, we postulated the Robot Enhancement Factors for each of his activities. Figure 4 depicts the day with his attendant as well as the projected day with a mobile assistant robot.

From the graph, it is clear that the total amount of time he could be functionally independent is dramatically increased by involving a mobile robot. A more significant finding is that the robot could carve out several large contiguous blocks of time during which R.Y. would need no assistance. These blocks of time would enhance his sense of privacy and allow for sustained periods of concentration and efficiency in his job. During the two 3-hour periods, the attendant would not need to be on stand-by to open envelopes, tear off computer printer output, and raise a glass of water. To establish these stretches of uninterrupted time alone is one important contribution a reliable robot system could provide.

An alternative REF-list would be needed to be able to generate a similar graph for a day with the desktop robot. It is obvious that activities involving the vehicle-functions would be eliminated, such as pushing elevator buttons and retrieving laser-printer output from the next room in the office building.

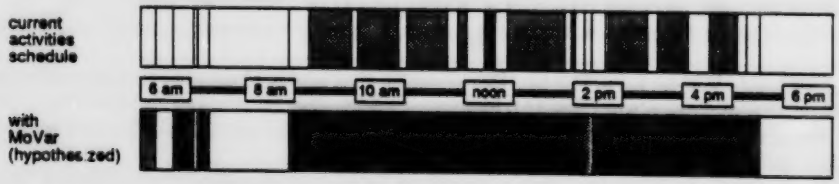

Figure 4. Influence of a Mobile Assistant Robot in the Workplace.
The two graphs show a person's functional independence level: Dependent = white; Semi-independent = light grey; Independent = dark grey. The top graph shows a C-3 quadriplegic's level of independence during a typical day's routine, including activities such as transferring, personal hygiene, commuting, his programming job, eating lunch, meeting with colleagues, and getting a drink of water. The lower graph projects his level of independence with a mobile assistant robot. Except for lunch-time activities, note the complete independence from an attendant during his entire work period.

DISCUSSION

We are developing a daily-activity profile of several quadriplegics in our community to measure the potential impact of an assistive robot on different life styles. Not all quadriplegics have jobs, but in a domestic environment, there are similar needs: opening mail, preparing a meal, brushing teeth, manipulating magazines and books, changing music cassettes, etc. These tasks need to be assessed, and the impact of introducing a robotic device, be it a desktop model or mobile, needs to be evaluated. The 128-item activity list needs to be enhanced to reflect vocational objectives, and the Robot Enhancement Factor lists needs to be expanded to include different system configurations.

In tandem, new robot sub-systems such as a sensate hand need to be examined in terms of these task-based studies. Can we project that a particular sub-system might have a major influence on the Enhancement Factor? Would an alternative design be safer or more versatile? We must also study which systems have the best ratio of benefit to cost, where cost is defined in terms of dollars, user mental effort, and task completion time, and benefit includes task completion as well as independence enhancement and an increase in privacy and quality of life. Early indications are that "low-cost systems" do not have benefit-to-cost ratios comparable to more "expensive" alternatives.

A related question that arises is: What is the minimal configuration, in terms of system autonomy and performance, that is acceptable to each potential user population? The answer, and its implication for system cost, is certainly important when prescribing robotic assistants to the disabled community. It is naïve to maintain that *any* level of enhanced independence will be appreciated, but exactly where the threshold lies, and what system attributes are influential, remain unknown at this time. We must prevent this development effort from falling victim to the all too common "assistive device ending up in the closet" problem.

CONCLUSION

As we consolidate our progress through system development and off-site evaluations, there are several research areas of particular interest to us. One centers on the increased operator workload typically encountered with an increase in system capabilities and complexity. It is difficult to provide direct user access to all low-level functions without complicating the human interface, thereby rendering the system unmanageable in terms of the operator's mental workload. There is a need, therefore, to develop computer-based language parsers to compile high-level user directives into available robot commands. This goal, formulated in the scope of a natural-language interface, is being addressed and has shown considerable promise [Crangle 88].

Based on our collective experience in rehabilitative robotics, we feel that the estimated REF values reported in this paper represent a first step in the direction of quantitative analysis of the effect of robotic technology on user independence. We will obviously need to perform the full task and field analyses to verify our hypotheses as well as our designs.

The technology development and clinical assessment trials of our robot prototypes have always involved significant input from our user population. We are now combining that empirical usage data with personal questionnaires and with a new assessment tool, involving the Robot Enhancement Factor, to more accurately assess the impact of the technology on the user's functional independence in society.

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"RESULTS OF A FEASIBILITY STUDY INTO APPLICATIONS FOR ADVANCED MEDICAL ROBOTS"

Patrick A. Finlay
Fulmer Research Limited
Hollybush Hill, Stoke Poges, SL2 4QD, United Kingdom

1. INTRODUCTION

The International Advanced Robotics Programme, which arose as a result of the 1982 Versailles Economic summit, included amongst its areas of study the application of advanced robotics (AR) to medicine and healthcare. The United Kingdom was appointed the lead country for this work area, with Canada, Japan and the USA as collaborators. Within the UK, a 12 month contract was awarded by the Department of Trade and Industry to Fulmer Research to carry out a feasibility study into possible applications.

The purpose of the study was to recommend up to 3 AR concepts in the medical/healthcare field, for which a market existed and a technical development programme could be devised leading to the production of an advanced medical robot. To qualify as a true AR device, a robot has to be capable of at least partially autonomous working in an unstructured environment.

The study has been guided by a Collaborative Group of some 40 interested parties from industry, healthcare and academic research, and was finally completed and accepted in March 1988.

2. SCOPE OF THE STUDY

The medical and healthcare field is a particularly wide brief, extending from preventive medicine through to diagnosis, treatment and rehabilitation. It includes care of the very young and very elderly, both at home and in institutional care, and embraces disciplines ranging from dentistry to psychiatry.

To cover this breadth of endeavour in a single study required careful planning. It was decided at an early stage to divide the subject into 5 broad medical areas:-

Diagnosis

Including mass screening, family doctor examinations, hospital examinations, pathology lab activities, imaging, endoscopy, catheterisation, and post mortems.

Patient Management and Services

Including condition monitoring, nursing, patient handling, peri-natal care, physiotherapy, surgery, operating theatre activities, hospital services, drug delivery, intensive care, barrier nursing, radiotherapy, infection control and emergency services.

Rehabilitation

Including work stations for the disabled, aids to daily living, prosthetics and orthotics, artificial organs, aids for the disabled living at home, aids for the visually handicapped and occupational therapy.

Gerontology

Including domestic services, monitor and response functions, preventive health care, alarms and mobility aids.

Pharmaceutical Manufacturing and Handling

Including preparation and packing of very high purity and very toxic drugs, clean room operations, laboratory research and development activities, pharmacy operations and waste disposal.

These areas overlap in some cases, and in other cases require a wide interpretation of their scope in order to include all relevant activities. Nonetheless, this division represented a useful split, not least because the technical requirements of advanced robotic devices in each area were usually quite different.

3. FEASIBILITY STUDY PROGRAMME

The programme drawn up for the feasibility study was divided into 3 phases: an idea generation phase, an information gathering phase and an analysis phase. The objectives of the study were to identify up to three advanced robotic concepts in the medical and healthcare field, to review the international state-of-the-art in medical robotics and to identify spin-off benefits in related areas resulting from medical AR developments.

The major constituent of the idea generation phase was a series of brainstorm sessions held on each of the five divisions of the subject. Each half-day session was attended by medical specialists, academics, equipment manufacturers and robotic technologists, and was advised by an expert in the relevant division. The result of this exercise was a list of some 400 possible ideas for applications of advanced medical robots.

In parallel with this activity, an international data collection exercise was carried out. This involved extensive literature and patent searches, as well as visits to major centres of medical robot development in North America, Japan and the U.K. Reports of visits to related European work were also collected. The information gathered from these sources formed the basis for a review of the state of the art, and was of course a valuable help in analysing the ideas generated in the brainstorm.

A panel of marketing, engineering and IT specialists then assessed the 400 ideas in the light of the information collected. A score was awarded in respect of several criteria, based on an Expected Total Net Benefit model with the form

$$V = P_T.P_C.\Sigma N\,(\Delta b - \Delta c) - D$$

where: P_T = Probability of Technical Success
P_C = Probability of Commercial Success
ΣN = Number of people affected
Δb = Increase in unit benefit, measured in QALY's for patients and carers
Δc = Increase in unit cost
D = Development cost

This model was an attempt to address the ethically complex area of relative values of different classes of treatment, and was based on the concept of the Quality Adjusted Life Year.

By applying successively tighter filters to the scores awarded to each idea, based on the principle of dominance, the original list was reduced to a few dozen ideas. These were then able to be grouped together to form a shortlist of 7 possible AR concepts. This shortlist then became the subject for analysis by medical, industrial and academic specialists, resulting in a final selection of 3 recommended proposals for further development.

4. PRESENT STATE OF THE ART: FINDINGS

As a general statement, it is the case that robotics has not yet penetrated the healthcare sector except in very primitive forms. There are exceptions to this observation, for example whole-body tomography scanners and a few specialised surgical devices, but mostly existing medical robots are low technology devices, thinly scattered in their application coverage.

There are several reasons for this. The most obvious is the fundamental difference between the requirements of (most) medical robots and industrial robots. Whereas the first safety principle of industrial robots is to prevent the machine contacting people, medical robots are actually required to interact with people, often in intimate ways such as feeding and eye surgery. Furthermore, the people concerned are frequently unable to take avoiding action should the robt develop a fault. Ergonomics and safety are thus primary concerns in medical robots, and technical performance is commonly down-rated to accommodate these needs, especially in the rehabilitation field. A related concern is legal liability for consequential injury caused by a defective robot or program. This rish has led to the virtual elimination of robot-assisted surgical procedures in the U.S. In the few cases where robots are used in that country, it is axiomatic that the robot never touches the patient.

A further important reason for the slow uptake of robotics in medicine is the supposed psychological attitude of patients. There is widespread sympathy with the view that a patient would rather be handled by a nurse than by a machine, and that a patient would react to a forthcoming surgical operation by a robot with some alarm. Although this view has not been tested, it seems intuitively credible. However, passengers are now happy to fly in aircraft controlled by auto pilots, and patients respond positively to artificial kidneys, automatic ventilators and infusion pumps when these are necessary. Furthermore, it is probably true that disabled and bed-ridden patients would welcome a device under their own control which enabled them to accomplish personal activities such as toiletry and bathing without outside help. A proper medical robot system design should take account of the patient's needs for human contact, and for reassurance that someone is there who can take control in the event of

malfunction but should be able to bring increased benefits to patients and carers by the effective application of technology.

A more difficult reason to justify for the absence of medical robots is the culture difference between engineering and medicine. The adoption of any new piece of equipment into medical practice depends on the existence of a clinician who is preparing to act as product champion. This is a risky proposition for the clinician, as his reputation stands to suffer if the equipment is unsatisfactory. The conservatism of clinicans is frustrating to equipment developers and to health service managers, who can see ready opportunities to increase patient care and reduce input costs using industrially proven technology. A more efficient mechanism for technology transfer into medicine becomes increasingly important as the patient demand for sophisticated automation increases.

Most current medical robot research is in the area of rehabilitation. In the U.S. and Canada there are several programmes devoted to robot work stations for the disabled and to development of static and mobile robot aids. Work on static robot aids for the disabled in the U.K. is taking place at Cambridge University and Bath Institute of Medical Engineering, and research in the same areas is being carried out in Holland and France. In Japan a robot guide for the blind is being developed, and other programmes are concerned with intelligent wheelchair control and a mobile fetch and carry robot. Prosthetics is a special subset of rehabilitation, and work on intelligent artificial limbs is underway in Japan. Powered prostheses of some sophistication are under development in the U.S., while work on artifical hands is in progress in several countries, Southampton University being a U.K. centre. Most of these devices suffer from the drawback of needing a heavy power supply to keep them functioning, and are constrained from wide acceptance by a high unit cost.

The area of patient management has attracted a small number of robot devices. A patient handling unit is under development in Japan, and a few examples of highly specific robot aids to surgery exist in Japan, the U.S., and especially Canada. Hospital services and transport robots are on the verge of introduction in several hospitals in the developed world. Prototype robot surgical instrument dispensers for operating theatre use have been developed based on existing educational robots.

In the diagnosis area, CAT scanners operating on robotic principles are in clinical use, as are radiotherapy source manipulators. A major thrust in this area is towards integrated hospital information systems, and the development of physician work stations for diagnosis incorporating PACS (Picture Archiving and Communication Systems) enabling several imaging modalities to be compared. Expert diagnostic systems are also becoming increasingly commonplace. Whilst not robotic in themselves, these developments are useful pre-cursors to a medical advanced robot.

Finally, in the field of pharmaceutical handling, current industrial robots are beginning to find applications, assisted by similar requirements in microelectronic fabrication clean rooms. Laboratory robots for R&D and quality assurance are also being introduced.

In all these areas, with the possible exception of the last, it must be said that scope exists for the introduction of even the present generation of industrial robots in considerable volumes to tackle current manipulation and control tasks. Much greater opportunity is presented to an advanced medical robot, able to cope with an unstructured environment and to work intelligently in co-operation with a human physician or patient. Current applications of robots to medicine are patchy and usually feature down-graded technology to compensate for safety or to reduce costs. There are considerable gaps in the market, which advanced medical robots will be well placed to fill.

5. PREFERRED CANDIDATES

The 7 shortlisted candidates which were selected by the assessment panel to be considered in detail were as follows:-

	Title	Examples of Application Areas
1.	Patient Handling Robot	Turning in bed; transfer to bed/chair/bath; portering.
2.	Fetch-and-carry Robot	Aids to Daily Living for handicapped; Occupational Therapy; theatre technician.
3.	Path. Lab. Robot	Frozen section and body fluid sample preparation and analysis.
4.	Surgery Robot	Post mortems; microsurgery; endoscopy.
5.	Intelligent Prostheses	Adaptive gripping; eye tracking; adaptive feeding.
6.	Monitor and Response Robot	Intensive care; barrier nursing; home help.
7.	Clean Room Operations Robot	Pharmaceutical manufacture; operating theatre decontamination.

These possible concepts were the ones which scored most highly in the analysis of all 400 ideas based on the model presented above.

3 advanced medical robot concepts were selected from this list, following detailed specialist discussions, as the recommendation of the feasibility study team to the Collaborative Group.

1. Fetch and Carry Robot for the disabled and elderly

Function

To carry out a limited range of tasks in a substantially unmodified home. An initial version of this robot would be capable of tasks like cooking and serving meals, household cleaning and environmental monitoring (e.g. hyperthermia, gas leaks, intruders etc.).

Concept

The robot would be tea-trolley sized and would carry 1 or 2 arms. It would be able to navigate freely around a home, avoiding furniture etc. Control would be remote, for example, by voice or keypad, and the robot would have sufficient intelligence to interpret commands like "bring me the red book".

Market (UK)

A. 237,000 elderly in institutional care: "hotel" costs $11,000/patient year to local authorities.

B. 13,700 disabled in institutional care: "hotel" costs $21,000/patient year to local authorities.

C. 1.33 million elderly live alone out of a total elderly population of 9 million.

Meals on wheels cost $1,000/yr to provide 1 meal/day.
Home help costs $700 - $3,000 depending on level provided.
5% of elderly living alone require over $4,000/year each in personal social services which a robot could replace.

Requirements

The robot requires general mobility in a home environment, including stair climbing and obstacle avoidance routines. Visual and tactile sensors are required for precision unstructured manipulation, and careful attention to the user interface in respect of safety, ease of communication and ergonomics is needed.

2. Patient Handling Robot for use in hospitals

Function

To transfer bedridden or immobile patients to wheelchair/bath/toilet etc. and to transport patients automatically between locations in a hospital.

Concept

A 150 kg capacity trolley fitted with 4-5 compliant blades which can be slid under a patient in order to lift him in a manner similar to a fork lift truck. Each blade can be moved independently to adjust the patient to e.g. a seated position. Control would be by a nurse with a key pad, who would initially ensure the blades avoided operating wounds etc. Once the patient was supported by the blades, automatic transport and transfer would be possible. In some cases, voice control by the patient without nursing assistance would be practical.

Requirements

A 150 kg capacity multi-arm compliant robot on a mobile base, with visual and tactile feedback and voice control. The robot must be capable of navigating in a semi-structured environment; conventional AGV technology is not sufficiently flexible.

Market (UK)

Average NHS bed occupancy 341,000 patients. Nursing consultants estimate 50% of these patients would require some handling assistance. This would require 13,500 robots.

Currently 750,000 nursing days are lost each year due to back injury - 2000 nurse years. A full fleet of robots would save a further estimated 5000 nurse years.

3. Surgery Assistant Robot

Function

1. To complement and assist a surgeon in precision microsurgical procedures.

2. To carry out procedures which would otherwise pose a risk to health care staff, under the remote control of a surgeon.

Concept

The precision manipulator (function 1) would be a human-arm sized robot clamped to the operating table, equipped with sensors and artificial intelligence software. It would be able to operate semi-autonomously, controlling depth of cut, suturing patterns and tissue discrimination using its own systems. Principle applications are in eye surgery, neurosurgery and intra-cranial investigations.

The tele-manipulator (function 2) would be a ceiling mounted arm able to cover the full area of the operating table. Its applications would include aspects of post mortems on infectious victims (AIDS, hepatitis, etc.) and radiotherapy.

Requirements

An advanced tele-manipulator with force reflectance and limited autonomy, able to be fitted with a variety of precision and effectors for tool manipulation. Mobility is not required, but a high level of sensory information must be capable of being processed in real time.

Market (UK)

Precision manipulator: applicable to about 120,000 procedures/year.

* Improved precision would reduce post-op beds, saving £95/patient day.
* Currently intractable procedures would be made possible, reducing care costs for patients treated.
* Progress would be improved by enhanced quality of precision surgery.

Tele-manipulator: 255,000 post mortems/year in 300 P.M. rooms.

65,000 radiotherapy procedures/year.

6. CONCLUSIONS

1. In the case of medical equipment, it is important to identify a clinical product champion who is prepared to be associated with the product during trials and initial launch. The eventual sales of the product, particularly in the first few years, depend critically on the credibility it has achieved through its association with an eminent practicioner.

2. Where equipment is likely to be purchased by private buyers, price sensitivity is liable to be high, whereas in the public sector purchasing priorities are determined largely on technical merit.

3. The three preferred and recommended Advanced Medical Robots are:

1. a fetch and carry robot for the disabled and elderly living at home,

2. a patient handling robot for hospital use,

3. a precision surgery assistant robot, with a hazardous conditions tele-manipulator as an intermediate product.

4. The market in the UK for these three proposals is shown in the table below. The UK represents about one thirtieth of the available world market. The world market is anticipated to show a growth rate of 15-20% per annum, based on the sales profiles of comparable medical automation products.

	Initial Annual Demand, Units	Price Sensitivity
Fetch and Carry	170	High
Patient Handling	140	Moderate
Precision Surgery	20	Low
Post Mortem Manipulator	4	Low

Summary of Expected UK Demand

5. The uptake of robots in medicine is negligibly small, and considerable scope exists for introducing robot technology to a variety of medical and healthcare tasks. The reasons for this low uptake in the past, particularly techno-fear and an inadequate dialogue between clinicians and engineers, have been overtaken by recent advances in other high technology medical equipment. The long-term future for automation in medicine appears buoyant when viewed in the context of demographic, social and technical trends.

MEDICAL ROBOTICS IN FRANCE

P. Rabischong
INSERM, Montpelier, France

MANUSCRIPT NOT AVAILABLE

THE MANUS WHEELCHAIR-BORNE MANIPULATOR.

H.H. Kwee and J.J. Duimel,
Institute for Rehabilitation Research, Hoensbroek;

J.J. Smits and A.A. Tuinhof de Moed, Product Center TNO, Delft;

J.A. van Woerden and L.W. v.d. Kolk,
Institute for Applied Physics TNO, Delft;

The Netherlands

ABSTRACT

An outline is given of the developments in the Dutch MANUS Project, highlighting elements of the mechanical, electrical and software designs. A first working model was realized to test design concepts, guiding the redesign towards a production model. The construction of three units of the latter one is under way. After a technical evaluation, a limited pre-production series will be realized, and some units may be made available to selected R & D centers.

1. INTRODUCTION

The objective of the Dutch MANUS Project is the development of a reasonably priced wheelchair-mounted manipulator with a modular computer-assisted control structure, adaptable to persons with severe disabilities of all four limbs. The design objectives and the control philosophy were discussed at the 1986 WRF-RESNA workshop on robotic aids (1). The functional elements are represented in fig. 1. The system consists of:

- o The mechanical arm mounted on the wheelchair.
- o Control transducers adapted to the particular user.
- o The firmware system for motor servo control, coordinate transformations, and control procedures to adapt the system to the human operator.

Technological developments are realized in close collaboration between the three institutes (represented by the authors) to achieve a high degree of integration of all system aspects (mechanics, electronics, computer hardware and software), in a trade-off between functional requirements and constraints on production costs.

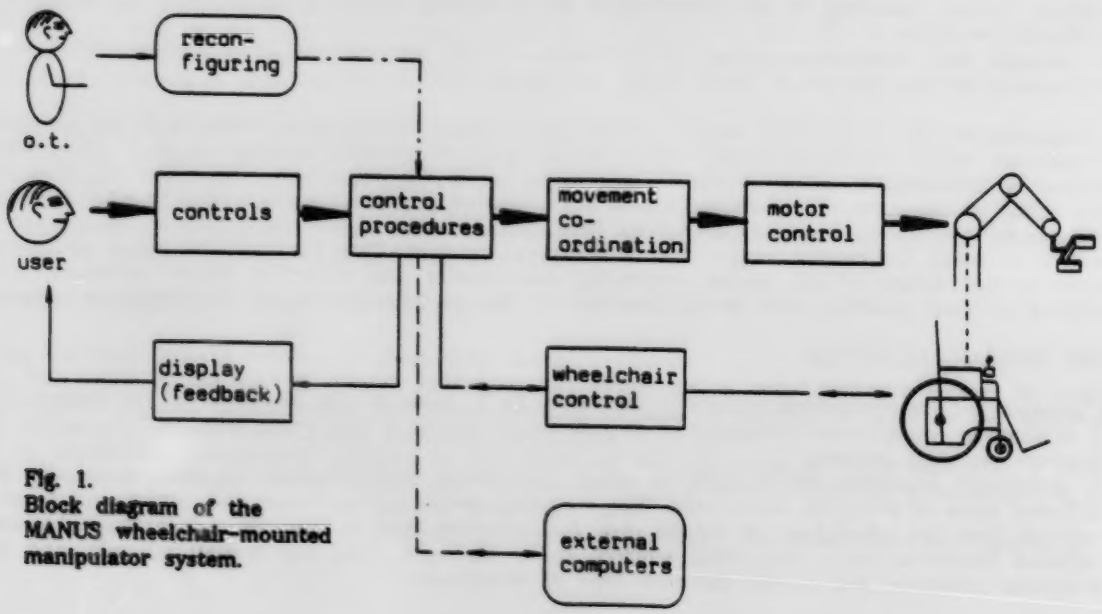


Fig. 1.
Block diagram of the MANUS wheelchair-mounted manipulator system.

2. CONTROL ASPECTS

The combination electric wheelchair and manipulator offers a functional compensation for the impairment of both mobility and upper limb functions. Individually selectable controls and reconfigurable microcomputer-assisted procedures are used to control both gripper and wheelchair movements in a unified way. Since the manipulator is mounted on the wheelchair, it is first of all intended to operate in an unstructured human environment of which it has little or no knowledge. Therefore much emphasis is placed on interactive procedures in which the user directly controls gripper (endpoint) movements and wheelchair displacements. In addition, a limited number of preprogramming and replay features will be offered to speed up or facilitate certain tasks. However, these computer-controlled movements will always proceed under close supervision of the operator, who at any moment will be able to influence the course of its execution or stop the movement. A display mounted near the gripper and a sound signal will provide an elementary feedback to the user to select control modes and to communicate various messages to him.

One of the modes will serve to control wheelchair movements, using the same controls and a specific interface to the particular wheelchair used. Access to external computers, again using the same controls and adapted procedures, may be realized in the future. When docked at a more structured working station, this might also be used to link the system to a local computer to speed up the execution of specific tasks, exploiting its knowledge of the specific situation.

An external computer, connectable through a serial interface, is already used to configure control procedures at different levels. At the "standard configuration" level therapists can select a control configuration from a library, and adapt its parameters to a particular user. If no appropriate configuration is available, higher levels give access to the tools necessary to construct new configurations, significantly different from those already available in the library, and which may then be added to the latter. In this way the functional possibilities offered will grow as more experience is obtained with different users, whose specific configurations may then be used for other persons with similar characteristics, individually modifying parameters where necessary.

Among the controls that may be used, we can mention a headrest control unit which is presently being developed. This unit can be used to control both manipulator and wheelchair movements, while maintaining a support for the head.

3. PRODUCT DEVELOPMENT

The product development has proceeded in two major steps:

- o A specification and preliminary design phase, defining the concepts and testing the options in various models, resulting in the construction of a working model of the system for a critical technical evaluation.
- o A redesign and construction phase, concentrating on the development of a product model and elaborating on the experience gained from the experimental model.

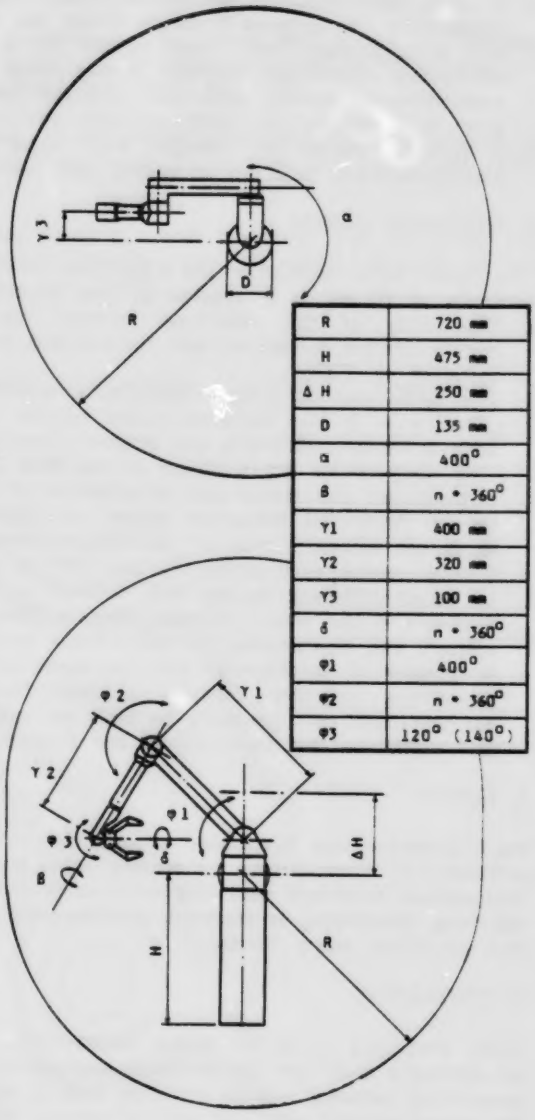
The evaluation of the experimental model showed that no basic changes were necessary in the concept, and indicated where continuing design efforts would be most effective in order to meet the design objectives of functionality, safety, cosmetics, production costs, life expectancy, and reliability. Whereas in the initial phases most of the design efforts were directed towards the more user-oriented aspects, in the second period extensive redesign efforts have been invested in the elaboration of those aspects necessary to make the system evolve into a consumer product. This has included rather extensive changes in the details of the design, increasing functionality and reliability where necessary, but simplifying it where possible, with special emphasis on the use of cost-effective production techniques.

4. THE MECHANICAL SYSTEM

The geometry of the mechanical system is shown in fig. 2. Some of the highlights of the design are:

- o A mechanical configuration consisting of an articulated arm on a telescoping base, with 8 degrees of freedom including gripping.
- o A wheelchair mounting kit is used to adapt the system both mechanically and electrically to different types of electrical wheelchairs. This mounting system allows for an easy attachment to and removal from the wheelchair. It can be used for mounting both to the left and to the right, and includes provisions for a removable armrest and a lapboard. Only one mechanical part, and an electronic interface, are specific for each type of wheelchair.

- The rotating and telescoping cylindrical base provides a vertical displacement of 250 mm of the shoulder joint, allowing objects to be fetched from the ground.
- The arm has a range of 720 mm at the wrist joint, or about 850 mm at the gripper.
- Objects with a weight of up to 1.5 kg can be lifted with a stretched arm. Exerted toques are limited by slip couplings on shoulder, elbow and wrist joint drives to protect both the user and the system against excessive forces. It also allows an attendant to passively push away the arm when necessary.
- The offset shoulder construction positions the upper arm further away from the user, providing more "living space". Together with the different lengths of the arm segments and the telescopic movement, it allows the arm to be folded away next to the column and stocked below an arm rest next to the wheelchair when not in use.
- Two of the three degrees of freedom at the wrist joint allow continuous rotations of the gripper.
- All motors and gear boxes are placed within the column to keep inertia down. The movements are transmitted to the peripheral joints through belt drives, gears and concentric hollow shafts, all contained within the arm enclosures.
- Mechanical uncoupling of elbow and shoulder movements and compensation of gravity forces allows for the use of small DC motor drives.
- A modular construction of the arm segments facilitates maintenance of the system.
- Aluminum castings and carbon fiber tubings have been used to reduce production costs and to keep the weight of the detachable manipulator unit under 20 kg. The new cosmetical design for the manipulator (not shown in fig. 2) is featuring more rounded shapes, integrated with aluminum casting structural elements of the segments of the arm. In view of the high investments necessary for the molds, only the most essential elements will be realized in this way for the first product models.
- A newly designed two-fingered gripper with adaptive elements assures a firm multi-point grip on objects with various shapes. Gripping force can be gradually increased under user control to a maximum of 30 newton. If necessary, the gripper can be passively opened by force by an attendant.



R	720 mm
H	475 mm
Δ H	250 mm
D	135 mm
α	400°
β	n • 360°
Y1	400 mm
Y2	320 mm
Y3	100 mm
δ	n • 360°
φ1	400°
φ2	n • 360°
φ3	120° (140°)

Fig. 2. Geometry and range of movement of the mechanical arm.

5. ELECTRONICS AND COMPUTER HARDWARE

The electronic system consists of three main parts:

- Two prints in the vertical column containing FET motor drives, opto-electronic sensors for angular position sensing of the joints, and communication circuits. In addition, a print in the upper arm contains the user displays and associated electronics.
- A control box permanently attached to the wheelchair and containing an 80186 computer, memories, transducer interfaces, power supply, and communication interfaces. A separate interchangeable print contains the interface for the specific wheelchair used.
- An external computer (IBM-PC) connected only to reconfigure the system but not required for its autonomous operation.

In addition, the following highlights of the design can be mentioned:

- o A serial communication system has been developed to link different subsystems through a two-wire connection. The original firmware design has been implemented in EPLD's and PAL's for the master and a proprietary gate array circuit for the slaves. This substantially reduces the problem of connecting subsystems through moving joints in tight spaces, simplifies the connection between the removable mechanical arm unit and the control box fixed on the wheelchair, and provides an electrically isolated link with controls, wheelchair electronics, and external devices.
- o A compact system for absolute joint angle measurement has been developed, using a two-track serially-encoded disk. An additional incremental encoder is used for interpolation and servo control.

6. SOFTWARE DESIGN

The object code resident in the wheelchair-borne system has to operate under real-time conditions at intervals of 20 ms. It is created in four modules on an IBM-PC environment:

- o The body of the real-time system, including servo controls, fast coordinate transformers, communication interfaces, and "patchboard functions" is compiled from a PLM source program and installed on PROMS.
  The servo control system includes a coordinate transformer within the loop for wrist position coordinates. It also includes vector velocity and gripper orientation control algorithms to maintain both movement direction and gripper orientation constant, even outside the linear operating range. This compensates for nonlinear effects from limited ranges of motor torques and velocities, which is of particular importance near singularities of the arm. In the same way, these algorithms are used to impose functional limits on vector velocities (while maintaining the direction of the movement). Maximum velocities may be individually specified in each user configuration.
- o Control modes, each giving the user control of a particular set of movements (1), and the procedure to select different modes, are defined in "patchboards", chaining together elementary functions available in the object program. Thus, a library of patchboards may be realized, using a "patchboard editor", and downloaded to non-volatile memory.
- o A number of patchboards may be made accessible to a particular user by some mode selection procedure, together forming a user "configuration". As mentioned, a library of different configurations may gradually be built up, optimized for different types of users, and easily accessable and modifiable by therapists in the field to adapt the system to a particular user.

7. SAFETY

Much attention has been paid to user safety, both in the mechanical design and in electronics and software (1). Thus, inertia of moving parts is kept low, slip couplings limit exerted torques, and an independent hardware watchdog continually checks software functioning. The software in turn checks watchdog functioning at start-up and continually checks critical communication links, servo parameters, and functional safety limits.

8. CONCLUSION

Three prototype units are under construction, one for its further development and evaluation as a rehabilitative tool, two for technical evaluation and industrial spin-off studies. In these units only the elementary software will be installed, and in particular an elaboration of the patcboard modules and of the reconfiguration tools will still be needed. Both these developments and studies with various disabled users should be persued after the successful completion of the technical evaluation of the prototypes. A limited pre-production series should be realized for these purposes. A few R & D centers have already expressed an interest in acquiring one of these units and participate in further developments. We would welcome a few other qualified R & D centers to join us in such a shared research effort.

ACKNOWLEDGEMENTS

The authors wish to dedicate this report to the memory of our friend and colleague Mr. Daniel W. Wijkmans. Following a request from the Muscular Dystrophy Association of the Netherlands, Mr. Wijkmans initiated this project, participated in its Directory Committee, and supported the teams with his valued advice.

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FIRST AUTHOR's ADDRESS

H. Hok Kwee, Ph.D., Institute for Rehabilitation Research, Zandbergsweg 111, 6432 CC Hoensbroek, The Netherlands. Tel. 31.45.224300.

A VOICE CONTROLLED ROBOT WORKSTATION FOR THE SEVERELY DISABLED

S.Y.D. Lee, R.E. Gander, and H.C. Wood
Department of Electrical Engineering
University of Saskatchewan

INTRODUCTION

Many individuals have physical impairments that are so severe that they are unable to interact with their surroundings effectively without the assistance of other people. There are estimated to be several thousand cases in Canada. Offering these people a way to learn and create independently would reduce the cost of long term health care. This would as well allow them to contribute to useful economic activity.

This work is toward the design and testing of a reliable workstation to help severely disabled persons so that they can manipulate a desk-top environment with a minimum of intervention from others. Common office tasks such as using books or files, operating a microcomputer with a keyboard, video display, and floppy disk drive, using remote controls, and filing printed material have been selected as the first target group of tasks for analysis. In the workstation, a robot arm is voice-controlled by the disabled person to achieve these operations. Any such system must be simple to use yet reliable and inexpensive.

SYSTEM ANALYSIS

It is important to perform a detailed analysis of the task requirements and to relate the requirements to the capability of available systems before any make-or-buy decisions are taken. In this way, unnecessary functions or complexity of the hardware can be reduced as much as possible. As a result, a minimum system configuration can be planned, and minimum cost approached.

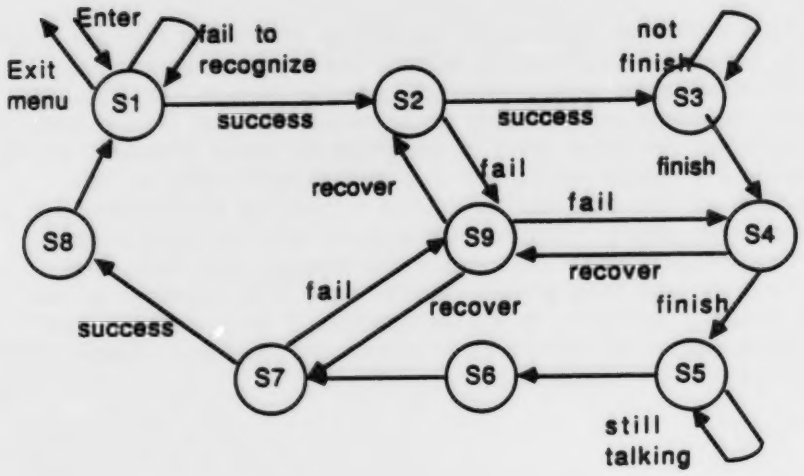
After considering typical operations in an office environment, the specific tasks given in Table 1 were selected for analysis and implementation.

Table 1. Task Names and Their Functions

Task Name	Function
1. Disk	Load and unload a computer disk drive
2. Shelve	Transfer a book to and from a book holder
3. Page turner	Turn the page of a book or bound file
4. Press button	Press control buttons such as on a keyboard or a remote control device
5. Turn knob	Handle rotational type of control knobs for appliances
6. Switch	Handle common types of switches such as paddle or rocker switches
7. Tape	Load and unload tape cassettes such as for a VCR or audio player
8. Telephone	Dial and receive telephone calls (rotary or keypad)

Task Requirements

Each task can be broken down into components or sub-tasks. Information is extracted from the analysis of each sub-task as a single task, and from the interactions among all the sub-tasks as a whole unit. For example, a receiving telephone call operation can be broken down into component states as shown in Figure 1.



LEGEND

S1: Recognize voice command from a menu of choices.
S2: Move robot arm to the telephone handset.
S3: Grasp the telephone handset.
S4: Remove telephone handset to desired position.
S5: Deactivate the voice recognizer to allow talking.
S6: Activate the voice recognizer.
S7: Transfer the telephone handset to the cradle.
S8: Return arm to home position.
S9: Perform positional error correction.

Figure 1. Simplified state diagram representation for receiving a telephone call.

Once a state diagram with determinant nodes is constructed, the following questions can be addressed:

- What are the possible requirements of success or failure in each node?
- What kind of sensors are needed?
- Can any sensor be replaced by the user's visual feedback?
- What kinds of errors can occur?
- What complexity in error recovery actions will be used?

The answers will depend upon the task knowledge that is available to the system.

After the detailed specifications for the performance to these tasks have been clarified, they can be translated into detailed requirements for the hardware and control software.

System Capability Requirement

The primary element of the workstation is a robot manipulator. The main interface is a voice recognition system, although an auxiliary interface, such as sip/puff switches, could be used to select alternatives according to the various forms and severity of disabilities.

The success of the task execution heavily depends on the robot system design. The requirements given in Table 2 summarize the features that need to be considered.

Table 2. Technical requirements of the robot system

I. Type of motion control
II. Work envelope
III. Speed requirement
IV. Payload of the manipulator
V. Positional accuracy and repeatability
VI. Type of gripper/tool
VII. Type of driving power
VIII. Degrees of freedom
IX. Mobility
X. Teaching method
XI. Sensor capability
XII. Robot controller capability
XIII. Interface capability
XIV. Voice control capability

The robot system requirements have been considered for each of the workstation tasks, and the results are given in Table 3. The functions across the Table, from 1 to 8, are those given in Table 1. The elements in the vertical column, from I to XIV, are those given in Table 2. The matrix elements of Table 3 are defined following the Table.

Table 3. Requirements Analysis for Workstation Robot.

Functions (Table 1) / Req'ts (Table 2)	1	2	3	4	5	6	7	8
I	C1	C1	C2	C1	C1	C1	C1	C1
II	C3	C3	C3	C3	C3	C3	C3	C3
III	30 s	60 s	2 s/p	2s/k	.1s/d	30 s	60 s	5-20 s
IV	300 g	5kgC4	200 g	500g	.02Nm	750g	500g	500g
V	2 mm	5 mm	2 mm	2 mm	2 mm	2 mm	2 mm	2 mm
VI	C5	C5	C7	C6	C5	C6	C5	C6
VII	C8	C8	C8	C8	C8	C8	C8	C8
VIII	C9	C9	C9	C9	C9	C9	C9	C9
IX	C10	C10	C10	C10	C10	C10	C10	C10
X	C11	C11	C11	C11	C11	C11	C11	C11
XI	C12	C12	C12	C12	C12	C12	C12	C12
XII	C13	C13	C13	C13	C13	C13	C13	C13
XIII	C14	C14	C14	C14	C14	C14	C14	C14
XIV	25 (words)	25	30	15	15	15	30	30,C15

C1: Non-servo point to point is not suitable.
Servo point to point is adequate

C2: Servo point to point is adequate when using a powered suction tool. Servo continuous will be more suitable when using a rubber-headed stick tool to turn pages

C3: Cylindrical, spherical, rectangular and jointed arm can be used, but jointed arm is more dextrous and helps to avoid collisions in a crowded desk-top environment.

C4: The mass of the book may be more than 5 kg.

C5: A parallel opening jaw with controllable width is desired.

C6: A simple short scissor type finger is adequate.

C7: A powered vacuum suction device or rubber-headed stick is required.

C8: Electrical drive is better than pneumatic or hydraulic, for quiet, clean, easy control, good resolution and a more readily available source of drive power.

C9: Six degrees of freedom or more are desirable, however for cost reasons five degrees can be used through careful planning of the desk layout.

C10: Mobility is not necessary for this desk-top environment.

C11: A manual teach pendant system would be beneficial to the programmer but not to the disabled user. The user should be able to teach the arm through voice control.

C12: Tactile sensors and vision could improve performance to some degree, however since the user's vision can provide feedback in most cases, object sensors can be avoided.

C13: The robot controller should be able to communicate and accept commands from a master computer. Each task will require at least two reference memory locations.

C14: RS 232C serial is sufficient.

C15: The voice recognition system can be isolated word, and speaker dependent. If the input is issued directly by related words, the average words required are displayed. An extra 26 phonetically distinct words may be needed to represent alphabetic characters when the user wants to edit or create name features.

The symbols s/p, s/k, and s/d represent seconds per page, seconds per key, and seconds per degree, respectively.

SYSTEM FEATURES

Robotic Hardware System

The requirements shown in Table 3 can provide a systematic way to facilitate make-or-buy decisions for a robot system. For demonstration in this project, a CRS-Plus M1 small industrial robot has been used. This robot meets most of the requirements although it has only five degrees of freedom (there is no wrist yaw). It therefore imposes some restrictions on the placement of objects on the desk. Moreover, the gripper is a short, pneumatically driven scissor unit that is not appropriate for transferring books and tapes, or turning knobs. A multifunction gripper is being developed as a separate project to complete the task requirements.

Speech Recognition System

The voice recognition unit is a speaker-dependent, isolated word Lisner 2000 system. It can recognize up to 64 words at a time, and it has a sample rate of 6.25 ksamples per second. Linear predictive coding and dynamic time-warping techniques are used in processing the speech signals.

Four interfacing schemes are used to connect the user to the system. These four techniques are as follows:

1. Related word: The user chooses directly using a related meaning word, e.g., 'telephone'.

   This input scheme is more natural, though the disadvantage in a low cost system is a high error rate when there are many alternative words.

2. Encoded word: The user chooses from a one or two dimensional command matrix encoded by numbers, or special keywords to reduce the size of the matrix.

3. Cursor Selection: The user moves the cursor in either one or two dimensions to a position over the desired command. The disadvantage of either of the direct selection techniques is that it is slower, however disabled persons who have difficulty articulating may find it useful.
4. Auto Scanning: This techniques is similar to cursor selection except that the cursor automatically moves through the command matrix under software control. This has the slowest response, however it provides the best alternative to compensate for limitations in the user, and it provides a very low cost system.

Carefully intermixing the four schemes results in a flexible system for a variety of users. If a particular user is stressed by misrecognition problems in the related word scheme, and performance is degraded, it may be advantageous to switch to the auto scanning mode for a while. Later, the user may be able to switch back to the faster related word method and be successful.

FEATURES OF TASKS

Control software has been developed to perform task oriented operations including handling the telephone, handling computer disks, and turning pages in books. Real time control software has been developed to handle errors that occur in the task oriented operations, and it is also used to test the actuation of buttons, switches, and knobs located at random positions in the work range of the robot arm. The following lists the features of those functions:

Telephone handling features:
- Create or edit a telephone directory menu
- Dial a call selected from the menu
- Dial a call input directly from the user
- Receive a telephone call
- Activate or deactivate the voice recognition for conversations

Computer disk handling features:

- Load and unload a floppy disk from a disk drive unit
- Change the orientation of a special diskette storage tray. (this tray is necessary for 5 1/4 in. flexible disks)

Page turning features:
- Turn a page from both directions
- Helping tool can be either a rubber headed stick or a vacuum suction device
- Adjust the starting and ending positions of the turner automatically when a preset number of pages is exceeded in one direction. It can also be adjusted by the user through voice interaction
- Able to handle different sizes of books and incline angles

Real time control features:

- Move in two motion modes: discrete and continuous
  Continuous motion can be stopped at a desired location when a 'stop' command is issued
- Resolution of the motion can be controlled by voice down to approximately 1 mm, or 1 degree for joint rotation.
- Move each of the five joints individually
- Move up, down, left, right, forward or backward from the wrist coordinate
- Move in the x, y, z direction in base coordinates
- Move up, down, forward, backward in gripper coordinates
- Open or close the gripper
- Repeat the last command issued
- Straight line motion mode
- Speed selection mode
- Teach mode to store, delete, or move to a particular location.

CONCLUSION

An analysis of the system design for a group of tasks specially selected for rehabilitation purposes has been conducted. The detailed specifications for the performance of these tasks have been developed and translated into requirements for hardware and software to obtain a minimum configuration for the system. A laboratory prototype meeting most of the requirements is currently being tested.

The wide spread use of the application does not necessarily depend upon more complex functions. Instead, simple, reliable, and inexpensive implementation is important, in conjunction with a thoughtful understanding of the tasks and abilities of the users.

Our continuing effort will be to evaluate and to improve the safety and efficiency of the existing system. In addition to developing a multifunction gripper for the desktop tasks, a five-fingered hand with tactile sensing has been built and tested in a separate project. It is available to determine the usefulness of such features to rehabilitation tasks that require greater resolution than can be provided by user feedback. Our goal is to assist disabled persons to access and control their surroundings whether for education, leisure, communication, or work for remuneration.

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CURL : A PROGRAMMING ENVIRONMENT FOR A REHABILITATION ROBOT

R.G. Gosine, W.S. Harwin, R.D. Jackson
Department of Engineering, University of Cambridge
Cambridge, CB2 1PZ, England

1.0 INTRODUCTION

There has been considerable effort in developing robot based manipulation devices to provide disabled people with greater control over the environment. The method of approach ranges from the development of telemanipulators offering the disabled person direct control of the robot to the establishment of semi-automated workstation environments requiring preprogrammed robot motion. The former approach uses the telemanipulator to replace the lost function of the disabled person and to restore the ability to manipulate the environment as desired by the person. In the latter approach, the robot may be used to automate sections of a manual task in order to create workplaces for disabled people in industrial environments. While both approaches have the common goal of increasing the degree of interaction between the disabled person and the environment, the underlying features of the robot systems are quite different. There is a particular contrast between the methods of programming the robot. Directly controlled telemanipulators, such as Spartacus and more recently Manus[1], provide the user with various reference frames in which to drive the end-effector. Since the telemanipulator is to be used in a highly unstructured environment little attempt has been made to introduce preprogrammed motions. The more structured approach of the semi-automated workstation involves preprogramming the robot to execute a series of motions to carry out a desired task. The form of preprogramming ranges from teach and replay programming[2,3], through the selection of preprogrammed motions[4,5], to the specially designed rehabilitation robotics language Calvin[6,7].

2.0 A ROBOT APPLICATION TO DEVELOPMENTAL EDUCATION

A current research project at the University of Cambridge is concerned with the investigation of a robot application to the developmental education of severely physically disabled children[8,9]. The majority of the children involved in the study suffer from cerebral palsy. For many of the children the telemanipulator approach is not appropriate, and a more structured workstation environment has been set up. There is a small group of children in the study who could benefit from the manipulator approach, and there are plans to integrate a form of direct control into the more structured workstation environment.

A number of educational tasks are being carried out during ongoing clinical trials. These include simple cause-effect tasks, colour and shape sorting, colour pattern matching, painting and game playing (Tower of Hanoi, Fox and Hounds). The tasks, which are developed with input from the special school teachers, are highly structured although the environment in which they are carried out may be relatively unstructured. Consider a simple colour sorting task requiring the child to sort a number of coloured blocks into corresponding coloured bins. The sorting task is structured although, in order to maintain the interest of child and the educational value of the task, the position of the coloured blocks and bins changes as the session proceeds. Most of the children involved in the study are capable of using single switches activated by the hand or foot, or a headswitch. With the more physically able children the method of input is a 12 key switch or, in one case, the child's communication device (Lightwriter).

The UMI RTX robot was chosen for the application after consideration was given to various other robots (eg. Mitsubishi, Puma). The RTX offers a good range of motion for an educational robot, and it is easily interfaced to high level control software. In addition, the RTX is a commercially available robot which was designed with consideration given to possible application in rehabilitation robotics settings. The current robot system consists of an RTX robot with a modified end-effector[10], a 68000 based vision system[11], and a Zenith 248 microcomputer. Communication with the robot is via an RS232 link and communication with the vision system is via an IEEE488 link. The disabled person interacts with the system via an RS232 link to a user interface. At present the user interface is a BBC microcomputer with software for decoding input from various types of input/output devices including single switches, multiple switches, headswitches, concept keyboards

and the Lightwriter communication device.

As mentioned previously, one reason for choosing the RTX robot for this project is the ease with which it may be interfaced to high level control software. The RTX comes with a Pascal library of explicit robot motion and communication routines which provides functions from initialising the robot's position to setting the force limit of the gripper. Clinical trials of the robot system in 1986 utilised this library in conjunction with a set of Pascal routines to carry out coordinate transformations and communicate with the vision system and the user interface. The application programs were written in Pascal and linked with the library provided with the RTX. As a result of the varying physical and cognitive levels of the children, the application program for even the most basic block stacking task required modifications during the clinical session in order to make the task appropriate for the child. Using the Pascal language to develop application programs required the programs to be recompiled after the modifications were made. As a result of the short attention span of many of the children who are using the robot, the time delays encountered in making simple modifications to application programs reduced the effectiveness of the robot in the developmental education application. In addition, the development of application programs using a general programming language such as Pascal requires an experienced programmer. It is more appropriate if the application programmer has a higher level environment in which to program the robotic workstation. This leads to easier programming of complex robotic workstations and provides nontechnical persons with the ability to create new application programs and modify existing ones. While it is probably not feasible that the disabled user would create the application programs, it is likely that therapists or school teachers with limited experience in computing could take advantage of such a programming environment. In response to the need for high level robot programming and the limitations imposed on existing application programming by the edit-compile-link-run requirement of languages such as Pascal, it was decided to investigate the application of robotic programming languages.

Forth Teach & Replay[12] and Calvin, two interpreted languages developed for high level RTX control, were evaluated. It was found that neither of these languages provided a suitable framework for the integration of sensor and vision information which is necessary if the robot is to carry out a structured task in a relatively unstructured environment. While Forth provides the programmer with a more interactive method for RTX programming than the standard Pascal library, the commands require explicit specification of the joint parameters and the language is specific for use with the RTX robot. The rehabilitation robot language Calvin was evaluated to assess the possibility of application as the robot control language. Calvin was undergoing a restructuring and, based on an uncertain the time scale for completion, it was felt that other options should be pursued.

3.0 DEVELOPMENT OF THE CURL ENVIRONMENT

3.1 CURL Version I

The interpretive robot control language CURL was initially developed as a tool to assist in the development of application programs in the clinical setting during a set of trials in 1987. CURL, which was written in Pascal and had a finite state machine structure, made a single pass through the application source code and executed the required sequence of robot motion routines to carry out the task. Equipment specific control routines were transparent to the application programmer and access to these devices was via general CURL primitives. The environment provided the programmer with facilities to create, edit, view and execute application programs written in a BASIC-like source code. The editor, which supported simple line editing, could be be invoked from within the environment although this feature was rarely used. Instead, a commercial screen editor was used outside the environment to create and edit application programs. While the interpreter approach proved successful in overcoming the problems encountered during the 1986 trials, it was evident that much work was needed in the structure of CURL. Error trapping and recovery were nonexistent and extension of the language was difficult. Despite its limitations, the CURL interpreter allowed for the modification and creation of application programs during the clinical session and enabled a larger number of children to use the robot than was possible during the previous trials.

3.2 CURL Version II

As a result of the success of the initial clinical trials of CURL , it was decided to formalise the requirements of the language and extend it to fulfil not only its requirement as a research tool but to look at possible integration into more general areas in rehabilitation robotics. In view of this intent it is fitting to term CURL a rehabilitation robotics language which serves as a flexible, high level programming tool for a robot operating in a rehabilitation workstation setting[13]. The philosophy taken in the development of CURL is to keep robot programming as simple, fast and interactive as possible. Hence, CURL has developed as a menu driven, task-oriented language with a relatively short command set, which provides the programmer with a high level, English-like software interface for robot programming . In order to provide an interactive environment CURL has been developed as an interpreter rather than a compiler. It is felt that some of the speed associated with compiled languages can be sacrificed for the programming flexibility of an interpreter. In addition, the interactive nature of an interpreter, which offers a simple but powerful command set, makes the system accessible to therapists or teachers having only a limited knowledge of computer programming.

4.0 STRUCTURE OF THE CURL ENVIRONMENT

The hierarchy of the CURL environment enables it to be used with various robots, vision/sensor systems and user i/o devices. There are three distinct levels within the CURL environment, (1) the *application level*, (2) the *interpreter level* and (3) the *device level*. The remainder of this section details these levels.

4.1 Application Level

The application level of the CURL environment provides the programmer with a convenient method of interacting with the robot system. This level is menu driven and the programmer is provided with options for completing tasks ranging from the creation of application programs to the initialisation of the robot's position. A number of useful programming features are incorporated into the menu structure. First, from within the CURL environment it is possible to invoke a screen editor to create and modify application programs in addition to files containing information about elements in the environment. This information about elements in the robot's environment is referred to as the *world description*. The inclusion of a screen editor is an improvement over the line editor of the original CURL interpreter.

Perhaps the most significant feature of the CURL environment is the facility for programming the robot in a task-oriented manner rather than in terms of explicit robot joint motions. If vision and sensor information is to be integrated into the motion planner for robots operating in an unstructured setting, the move away from explicit robot programming toward more task-oriented programming is essential. In task-oriented programming the programmer specifies the task to be carried out as opposed to the sequence of robot joint motions necessary to complete the task. Task-oriented programming has been predicted to form the basis for the next generation of robot programming languages[14,15]. Many industrial robot languages, such as Unimation's VAL which is one of the most widely used robot programming languages, do not support task-oriented primitives. A recent language from Unimation, VAL-II[16], and other robot languages, such as RCCL[17] and PAL[14], support coordinate frame assignments which lead to a more task-oriented approach but fall far short of providing a task-oriented programming environment. Many of the current industrial robot languages are robot specific or have fixed primitive sets which can not be expanded to meet the requirements of a rehabilitation robot language. CURL has been designed to be robot independent and has a primitive set which can be modified and expanded.

4.1.1 Programming Constructions

This section gives a brief description of the programming features of the CURL language: program structure, variables, world description, control of flow and robot system primitives. It is not the intention to give an exhaustive explanation of the structures but rather to give an overview of the CURL language.

4.1.1.1 Program Structure

A CURL program comprises one or more program blocks containing application code. The two types of program block structures in CURL are the *procedure block* and the *main program block*. Application code may be made up of any programming constructions in the current CURL instruction set. Each application program has zero or more procedure blocks followed by a single main program block. The main program block can

access the code in any of the procedure blocks defined within the application program. The CURL structure is similar to the Pascal structure in that procedures are able to contain calls to procedures defined before it in the source code. In addition, the passing of parameters between program blocks is supported.

4.1.1.2 Variables

It is through the use of *variables* that CURL keeps track of numbers and world descriptions. CURL is structured such that variables are allocated space in the symbol table when they are first recognised by the interpreter. This generally occurs at the first instance of the variable in the application program. When a variable is allocated space in the symbol table it defaults to reference an integer and it is assigned a numeric VARIABLE type. The value of the variable is initialised to 0.

It is possible to override this default declaration and define variables which describe elements in the world environment. Details of specifying the world description are presented in section 4.1.1.3. It is sufficient to say that the commands **OBJECT** [*variable*, ...] and **GOAL** [*variable*, ...], result in changes to the contents of the symbol table entry for *variable*. Consider the following statement:

OBJECT [**block1**, *parameterlist*];

When the CURL interpreter recognises this statement, the symbol table entry for the variable **block1** is symbolically linked with a data element defined by the contents of the *parameterlist*. After the execution of this statement, the variable **block1** contains a description of an object in the robot's environment.

4.1.1.3 World Description

As an extension to numeric VARIABLE types, CURL offers the application programmer a means by which descriptions of elements in the robot environment can be specified. There are two types of variables which may be defined using world descriptions. First, OBJECT types are given to variables that are used to identify elements in the robot's world that are to be manipulated by the robot. Secondly, GOAL types are given to variables that are used to identify locations in the robot's world.

To extend this concept further, the elements in the robot's world may be linked such that a change in the position or orientation of one element transforms the position and orientation of any elements that are linked. This ability to specify an affinity between elements is a powerful feature of CURL in providing a task-oriented programming environment. There are many situations where this feature is desirable and even necessary. Consider an application in which a camera is to identify a marker attached to a paint palette and provide information concerning the position and orientation of the palette to the robot system. The position and orientation of the marker is of little concern to the application programmer who requires information about the locations of the various paints on the palette. In cases such as this it is necessary to be able to specify an affinity between the position and orientation of the marker, which the vision system can identify, and the positions and orientations of the various paints on the palette.

Variables having OBJECT and GOAL types are declared using CURL world descriptions having the following form:

OBJECT [*name*, x, y, z, θ_{z1}, θ_{y2}, θ_{z3}, *height*, *affinity factor*];
GOAL [*name*, x, y, z, θ_{z1}, θ_{y2}, θ_{z3}, *height*, *affinity factor*];

When the CURL interpreter recognises such a definition it forms a link between the symbol table entry for *name* and a structure in the data base which contains the declared attributes of the data element. In addition, the interpreter asserts a flag associated with the data element. This flag, which may be interrogated and toggled by the application programmer, is particularly useful in control of flow structures. The parameters contained in the world description consist of (1) the *name* to assign to the variable, (2) the cartesian coordinates of the origin of a reference frame attached to the element (x, y, z) , (3) the Z-Y-Z Euler rotation of the reference frame attached to the element (θ_{z1}, θ_{y2}, θ_{z3}), (4) the *height* of the element, and (5) the *affinity factor* having a value equal to the number of elements having an affinity to the data element. In the CURL language, the position and orientation of an object, a goal, and the robot end-effector is specified in terms of robot independent cartesian and euler parameters.

When affinity is established between data elements, a transformation of the position and orientation of

an element results in a relative transformation of the position and orientation of any data elements having an affinity to the transformed element. Furthermore, it is possible to specify the position and orientation of a data element with respect to another data element without creating an affinity between them. This may be specified using the following CURL construction:

RELATIVE [*name2, name1,* $x, y, z, \theta_{z1}, \theta_{y2}, \theta_{z3}$]**;**

This construction updates the position and orientation of *name2* to correspond to the position and orientation of *name1* transformed by the following vector:

$$[\ x,\ y,\ z,\ \theta_{z1},\ \theta_{y2},\ \theta_{z3}\ ]^T$$

Further transformation of the position and orientation of *name1* will not cause any changes to occur to the position and orientation of *name2*.

4.1.1.4 Control of Program Flow

As a structured programming language similar in many respects to Pascal and C, CURL offers a number of constructs to allow the programmer to control the flow of an application program. These include (1) conditional branching, (2) conditional looping and (3) unconditional looping.

Conditional branching involves the execution of a section of application code only if a certain condition is satisfied. This type of action is specified in CURL using an **IF statement** having the following form:

IF [*conditional statement*] { *application code* }
ELSE { *application code* }

The repeated execution of a segment of application code as long as a certain condition is satisfied is termed conditional looping. The **WHILE statement** is offered in the CURL environment as a means for programming conditional loops. The general form of the WHILE statement is:

WHILE [*conditional statement*] { *application code* }

Unconditional looping involves the execution of a section of application code a predefined number of times. This may be programmed using a **FOR statement** having the following general form:

FOR [*counter_variable* = *initial_value* **TO** *final_value*
STEP*increment_value*] {*application code* }

Conditional looping and branching control the flow of an application program based on the value of the *conditional statement*. The conditional statement, which evaluates to be **TRUE** or **FALSE**, may be any legal variable, expression or statement. In addition, variables, expressions or statements linked by standard logical and relational operators comprise valid conditional statements. It is planned to introduce conditional statements which would support positional operators, such as **ON**, **UNDER** and **NEXT_TO**, in a future version of CURL.

4.1.1.5 Curl Primitives

The CURL programming environment provides the application programmer with a number of primitives for controlling the robot system. The primitives currently supported include:

(1) TAKE_PICTURE [*number of objects seen*];
(2) USER_INPUT [*device, response*];
(3) PITCH [*degrees*];
(4) ROLL [*degrees*];
(5) MOVE_TO [*cartesian-euler coordinates*];
(6) MOVE_TO ABOVE_OBJECT [*sensor mode, object name*];

(7) MOVE_TO OBJECT [*sensor mode, object name*];

(8) MOVE_TO ABOVE_GOAL [*sensor mode, goal name*];

(9) MOVE_TO GOAL [*sensor mode, goal name*];

(10) GRASP [*jaw separation*];

(11) GRASP [*object name*];

(12) RELEASE [*object name*];

While the action of each of these primitives is evident from the grammar, it is worth taking a closer look at some of the primitives. The **TAKE_PICTURE** primitive activates a set of routines to communicate with the vision system computer and process a picture of the work area. The primitive updates the contents of the data base to reflect the information gathered from the vision call. In addition, the number of objects seen during the vision call is returned and may be used in the application program. The **USER_INPUT** primitive enables the programmer to specify input from a number of devices in the application program. The programmer specifies the device to be interrogated (*device*) and the primitive returns the input value (*response*).

Primitives (6) to (9) provide a means of locating the robot end-effector at the position and orientation of an object or goal which has been previously defined in the data base. The primitives including the ABOVE_OBJECT and ABOVE_GOAL keywords locate the end-effector 100 mm along the z axis of the reference frame attached to the object or goal. These primitives also account for the height of the object or goal, in addition to the height of any object in the end-effector, when calculating the required position and orientation of the end-effector. The parameter *sensor mode* specifies the course of action to be taken in carrying out the primitive. In mode 1 sensory feedback, in addition to information stored in the data base, is used to locate the end-effector at the grip site of the specified object. In mode 0 no sensory feedback is used in locating the grip site.

There are two forms of the **GRASP** primitive. Primitive (10) accepts a parameter specifying the desired jaw separation in mm, while primitive (11) accepts a parameter specifying an object which has been previously defined in the data base. The CURL interpreter requires that the end-effector does not contain any object when it attempts to grasp the specified object. In addition, the end-effector must be located at the grip site of the object before a grasp is attempted. A successful grasp causes the end-effector to close on the object and an affixment of the object to the end-effector is recorded by the interpreter.

The **RELEASE** primitive, which is intended for use in conjunction with the **GRASP** primitive, checks to ensure that the object being released, *object name*, is affixed to the end-effector. In addition to releasing the object from the end-effector, the interpreter updates the position and orientation of the object in the data base. Data base entries for objects having an affinity to the released object are also updated.

In addition to the above mentioned primitives, a number of other primitives are under development. These include:

(1) DRIVE [*mode, device*];

(2) MOVE *object name* **TO** *goal name*;

(3) DEFINE *object name* **AT** *goal name*;

(4) DEFINE *object name* **ON** *object name*;

The **DRIVE** primitive will provide direct control of the robot with a variety of modes of control (ie. cartesian, r-θ, joint) using a number of input devices. The **MOVE** primitive will allow the programmer to instruct the robot to move to and pick up the object specified by *object name* and move it to the location specified by *goal name*. The data base will be updated to reflect the new location of the object and the new contents of the goal. Primitives (3) and (4) will provide the programmer with further means of specifying relationships between objects and goals in the workspace.

4.1.2 Off-line Program Development

CURL offers the application programmer a method for checking the syntax, the semantics and the flow of an application program before executing the program with the robot or vision system. In the off-line mode,

the application program is interpreted by the CURL preprocessor in the same fashion as during the execution of the application program. Unlike normal execution of an application program, any device related CURL commands are directed to the screen rather than to the device. Syntax and semantic errors are reported to the programmer on a special error report screen. The errors are reported with a reference to the line number in the source file containing the error along with a brief description of the error.

4.2 Interpreter Level

The primary tool used in developing the CURL interpreter is the language development system Yacc[18] which provides a convenient framework for specification and modification of the grammar and the construction of the parser. The three major components of the interpreter are (1) the lexical analyser, (2) the parser and (3) the semantic actions. In addition, a data base containing the runtime description of the robot environment is a component of the interpreter level of CURL. Execution of an application program involves two passes by the interpreter. During the first pass, the syntax and semantics of the application code are checked, and an intermediate representation of the code is generated. The second pass involves the execution of the actions implied by the intermediate representation. The lexical analyser carries out the first level of processing on characters from a source file containing application code or from the keyboard. The analyser is a finite state machine designed to convert predefined character sequences into tokens representing CURL keywords, numbers, variables, mathematical operators, etc.. In addition, the lexical analyser initialises variable entries in the symbol table upon recognition of a variable and ensures that any character sequence having a keyword format (uppercase) corresponds to a valid keyword.

The parser is responsible for ensuring that the sequence of tokens from the lexical analyser obeys the grammar rules of the language. Like many interpreters and compilers, the CURL interpreter creates an intermediate representation of the input code. The intermediate code is generated during the first pass through the interpreter by semantic actions associated with the various grammar rules. During the second pass of the interpreter, the intermediate code is translated by a second set of semantic actions into the operations specified by the source program. If there are any syntax or semantic errors detected during the first pass through the interpreter these are reported to the programmer. The parser then attempts to correct itself and minimise the effect of the error so that the remainder of the source code may be parsed. If errors are detected during the first pass through the interpreter, the second pass is aborted.

A dynamic data base containing the world description is created and maintained during the second pass of the interpreter as a result of the semantic actions associated with the various definitions and primitives in the source code. Robot and vision/sensor system shell functions are also part of the interpreter level. These device independent functions define the information to be passed into and received from the device dependent driver routines.

4.3 Device Level

The device level is the lowest level in the CURL structure and is the only level which varies according to the system configuration. Robot driver routines accept general robot independent motion commands, calculate kinematic transformations, convert joint parameters into motion commands as defined by the robot protocol, communicate with the robot using robot specific communication protocols and interrogate internal robot sensors to ensure that high level motion commands are carried out successfully. Vision/sensor driver routines are responsible for communication with the vision/sensor control computer. Information received from the vision/sensor drivers ranges from end-effector sensor data, which is used by robot driver software to augment the internal robot sensor data, to vision information, which is passed to interpreter level software responsible for maintaining the data base. Any link between the interpreter level and the device level is coordinated by robot and vision/sensor shell functions at the interpreter level.

5.0 EXAMPLE PROGRAM

The sample CURL application program given in Figure 1, which illustrates many of the ideas presented in section 4.1.1, enables a disabled person to play the game Connect4. The game normally requires good hand control in order to insert small discs into slots on the Connect4 frame. Through the use of a headswitch, the disabled child selects slots into which the robot places red discs. The game continues until the child has

placed 15 red discs in the Connect4 frame. The sample program illustrates the concepts of procedure and main program blocks, parameter passing, declaring the world description, conditional branching, unconditional looping, conditional looping, user input/output and a number of robot system and vision system primitives. Note that comments are delimited by question marks.

```
? program to play Connect4 using headswitches ?
PROCEDURE move_to_slots[%slot_no1, %slot_no7];          ? start of a procedure block accepting 2 GOAL type parameters ?
headswitch = 4;                                         ? child using headswitch for i/o ?
open = 70;                                              ? gripper open = 70 mm ?
dropped=0;                                              ? disc not dropped ?
sen_off = 0;                                            ? sensors disabled ?
GOAL[slot,0,0,0,0,0,0,0,0,0];                           ? dummy variable used as a counter ?
WHILE[dropped=0]{                                       ? continue to loop until disc is dropped ?
    FOR[slot=slot_no1 TO slot_no7] {                    ? index through the 7 slots ?
        IF[dropped=0]{                                  ? check if disc has been dropped ?
            MOVE_TO GOAL [sen_off,slot];                        ? no, move to the next slot ?
            USER_INPUT [headswitch, childs_response];           ?get response from child ?
            IF[childs_response]{                                ? check if child wishes to drop disc ?
                GRASP[open];                                    ? yes, open gripper and release the disc ?
                dropped=1;                                      ? flag indicating disc has been dropped ?
}}}}
END_PROCEDURE;                                          ? end of procedure block ?

MAIN;                                                   ? start of the main program block ?
OBJECT [disc_tray_id, 0, 0, 0, 0, 0, 0, 80, 1];         ? define id marker on disc tray ?
    OBJECT[ red_disc, 0, 0, 0, 0, 0, 0,67, 0];          ? define red disc wrt disc tray ?
OBJECT[ next_disc,0, 0, 0, 0, 0, 0, 0, 0];              ? variable for next disc on the tray ?
OBJECT[ connect4_frame, 0, 0, 0, 0, 0, 0, 0, 0];        ? define id marker on the Connect4 frame ?
GOAL[slot1,0,0,0,0,0,0,0,0];                            ? define the 7 slots at the top of the Connect4 frame ?
    GOAL[slot2,0,20,0,0,0,0,0,0];                       ? define slot2 wrt slot1 ?
    GOAL[slot3,0,40,0,0,0,0,0,0];                       ? define slot3 wrt slot1 ?
    GOAL[slot4,0,60,0,0,0,0,0,0];                       ? define slot4 wrt slot1 ?
    GOAL[slot5,0,80,0,0,0,0,0,0];                       ? define slot5 wrt slot1 ?
    GOAL[slot6,0,100,0,0,0,0,0,0];                      ? define slot6 wrt slot1 ?
    GOAL[slot7,0,120,0,0,0,0,0,0];                      ? define slot7 wrt slot1 ?
shut=30;    open=70;                                    ? gripper closed = 30 mm , gripper open = 70 mm?
sen_off=0;  sen_on=1;                                   ? sensors disabled/enabled ?
no_of_red_discs = 15;                                   ? number of red discs ?
WHILE [ no_seen < 2 ] {                                 ? ensure that the connect4 frame and disc tray are seen ?
    TAKE_PICTURE[no_seen];                              ? trigger vision processor/update data base ?
}
RELATIVE [slot1, connect4_frame, 340, 0, 90, 90, -90, 0];   ? slot1 wrt connect4_frame ?
FOR [i=1 TO no_of_red_discs] {                          ? for all red discs ?
    GRASP[open];                                        ? open gripper to 70 mm ?
    MOVE_TO ABOVE_OBJECT[sen_off,red_disc];             ? move above tower of red discs ?
    MOVE_TO OBJECT[sen_off,red_disc];                   ? move to red disc at top of tower ?
    GRASP[shut];                                        ? close gripper to 30 mm ?
    MOVE_TO ABOVE_OBJECT[sen_off,red_disc];             ? pick up the top disc ?
    move_to_slots[slot1, slot7];                        ? procedure to select a slot ?
    RELATIVE[next_disc,red_disc,0, 0, -7,0, 0, 0];      ? next disc in tower is 7mm below current top of tower ?
    RELATIVE[red_disc,next_disc,0,0,0,0,0,0];           ? new height of disc tower ?
}
END;                                                    ? end of main program block ?
```

Figure 1 - Sample CURL Program

6.0 CONCLUSIONS

The CURL programming environment has been developed in response to a lack of flexibility encountered in programming the RTX robot using conventional programming languages. CURL has been successful in providing a flexible robot programming environment. This success may be measured in terms of the ease with which application programs may be created and modified, and in terms of the ability to modify and extend the underlying structure of the interpreter. While the current grammar has evolved from the requirements of the robot operating in a developmental education setting, it is general enough to have an application with robots operating in a general workstation environment. The task-oriented features of the language make CURL a unique environment in which to program robots for rehabilitation applications. With the inclusion of primitives related to direct control of the robot, CURL will close the gap that currently exists between the telemanipulator and the preprogrammed robot approaches.

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A ROBOT WORKSTATION FOR THE DISABLED

M. R. Hillman and R. D. Orpwood
Bath Institute of Medical Engineering,
Royal United Hospital,
Bath, United Kingdom

1. PROBLEM STATEMENT

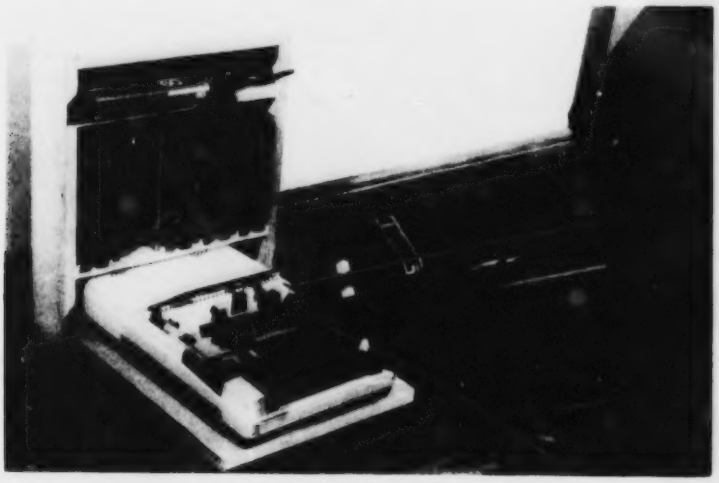
For the severely physically disabled person, particularly those with little or no hand or arm movement, the ability to control their environment is very important if they are to retain any independence. Environmental control systems (ECS) fulfil an important role, but can only be used with preselected pieces of equipment which are electrically operated. Most manipulative tasks are therefore precluded from control by an ECS. The use of a robotic manipulator is proposed to overcome these limitations.

Any practical aid for the disabled must be made available at a price that can be afforded. The aims of the Bath Institute of Medical Engineering (BIME) are to produce equipment in the short to medium term, rather than to follow long term research. For this reason the robot system which has been designed at BIME is a workstation based system, initially using a relatively inexpensive robotic manipulator.

2. APPLICATION AREA

A simple workstation will only be able to carry out a limited number of tasks due to both the limited mobility of the robot and limitations of the gripper control and mechanism. Because of such limitations a simple workstation robot system will be mainly of use for the very severely physically disabled, particularly those with limited arm or hand ability.

At an early stage in the project a survey was made of potential users to determine the disabilities concerned and the needs and potential tasks which the device might perform [Clarke et al. 1]. Forty two subjects were interviewed in the Bath area - all of these people had either limited or no upper limb ability. Twenty five of these people were Multiple Sclerosis sufferers and 10 had spinal lesions.



Cassette being loaded into player.

Fig.1

All but four of the 42 subjects were either being permanently cared for in a hospital or an institution or had a partner caring for them at home. The probable user is therefore likely to be someone who is generally cared for, but wants a degree of independence. For a person living at home with a spouse (or other full-time helper) the robot would be able to provide a certain degree of independence for the disabled person, and allow the carer more freedom, perhaps to go out for the afternoon.

It was found that all the subjects would be able to use a two-switch input (for example a microswitch or suck-blow switch), and seven were familiar with this as a form of input for the control of an Environmental Control System. All but five of the subjects were able to use a joystick, and many were familiar with this as a means of controlling an electric wheelchair.

The survey showed that the most popular occupations were watching TV or reading. Some of the subjects had special hobbies and interests, but only three were in any kind of employment. Typical tasks suggested for a robot aid were kitchen use, particularly making a hot drink, feeding, picking items up from the floor and loading a cassette tape.

The decision to build a relatively simple desk top mounted device precludes some of the tasks mentioned above. For example the reach is likely to be insufficient to pick up items from the floor, and tasks requiring complicated manipulation will not be feasible. It is intended however to incorporate a number of tasks onto the workstation to produce what may be a useful and cost effective device.

3. RESEARCH COURSE

The research was divided into an initial feasibility study and a subsequent detailed development phase. The feasibility study examined the problems of controlling a multi-degree of freedom device using only a two input control and then evaluated the system in users homes, with the robot arm configured to carry out a few simple demonstration tasks, such as illustrated in Fig. 1. In the detailed development phase a complete and self contained workstation system is being built, incorporating lessons learned from the feasibility study. The device will be evaluated during longer term trials and developed up to the point where commercial production can commence. In particular the arm will be redesigned from experience with the commercially available robot in this particular application.

4. METHODS USED

In the feasibility study (reported in greater depth in [Hillman. 2]) a simple system was constructed which could be transported to the homes of disabled people for trials (Fig. 2).

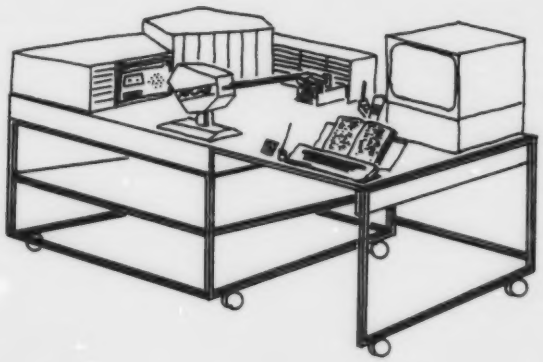
Robot trials in user's home.

Fig.2

At this stage a commercially available educational robot was used. The robot arm was the "Atlas" arm, produced by L.J. Electronics of Norwich, UK. This was chosen for its good load carrying capacity and rigidity at reasonable cost. Software was written on the BBC Microcomputer, in machine language for the robot control routines and in BASIC for the user control, so that it could be easily modified. This enables the robot to be driven in real time using a two switch controlled menu system. The screen presentation for the menu was arrived at after preliminary trials with disabled users, using a 2-D screen representation of the robot. The software also enabled simple routines to be produced for the robot to carry out repeatable tasks.

The system under current development is a total workstation, on a trolley. The robot manipulator is still at this stage the Atlas robot. The controlling hardware is still the BBC Micro.

The trolley is to be approximately 1.7m by 0.9m, and will incorporate all the equipment for the tasks originally envisaged. This will include a computer with separate keyboard, which will be operated by mouthstick (this being the method of computer use favoured by the Occupational Therapists with whom we are working), discs and double disc drive, a cassette player, books and magazines which may be transferred to a book rest for pages to be turned by a mouthstick, and a telephone. Other tasks will be added as the trials progress. The workstation is illustrated in Fig. 3.

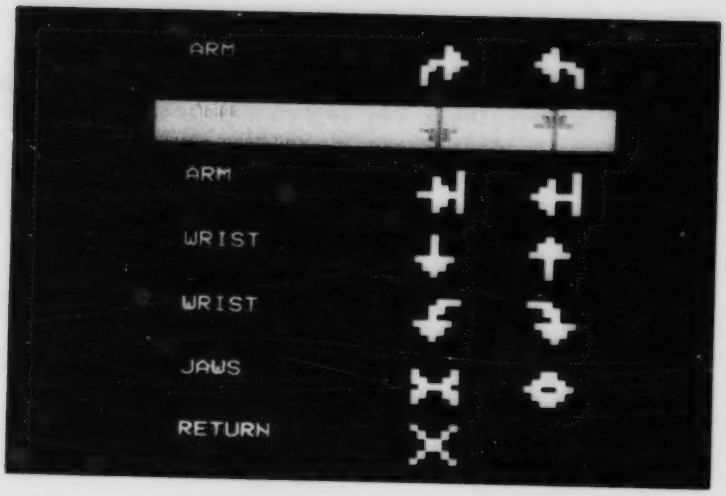


Proposed layout of workstation.

Fig.3

The basic Atlas robot has five degrees of freedom, plus gripper open/close, all of which are stepper motor driven. The arm movement is polar, within a spherical working volume. One of the problems with the feasibility system concerned noise and speed of movement when more than one motor were in operation. Part of the reason for this was that with the original electronics the stepper motors could only be stepped sequentially with pulses from the computer. The control electronics have been redesigned so that latches relating to the individual motors are initially loaded with the required speed and direction. Each motor will then run independently of control signals until the value in the latch is changed. This allows the motors to run in parallel independently of each other. The gripper is also being redesigned and will incorporate at this stage a simple force sensor to restrict the force applied by the jaws.

The software is being written in machine language, and will be put on EPROM. Following the success of the feasibility study, it will be possible to control the robot in real time from a symbolic scanning menu (Fig. 4) using a two switch input. There will however be a much greater emphasis on the use of stored routines (which will be stored on battery backed sideways RAM). The routines will be created by moving the robot in real time, but may then be edited from the keyboard (possibly by the disabled person using a mouthstick). A feature of the earlier system, which is to be extended, is to allow the user to interact with the robot during the replay of routines. For example when using a pre-programmed routine to place a tape in a tape player it is possible for the user to adjust the position of the tape precisely if it

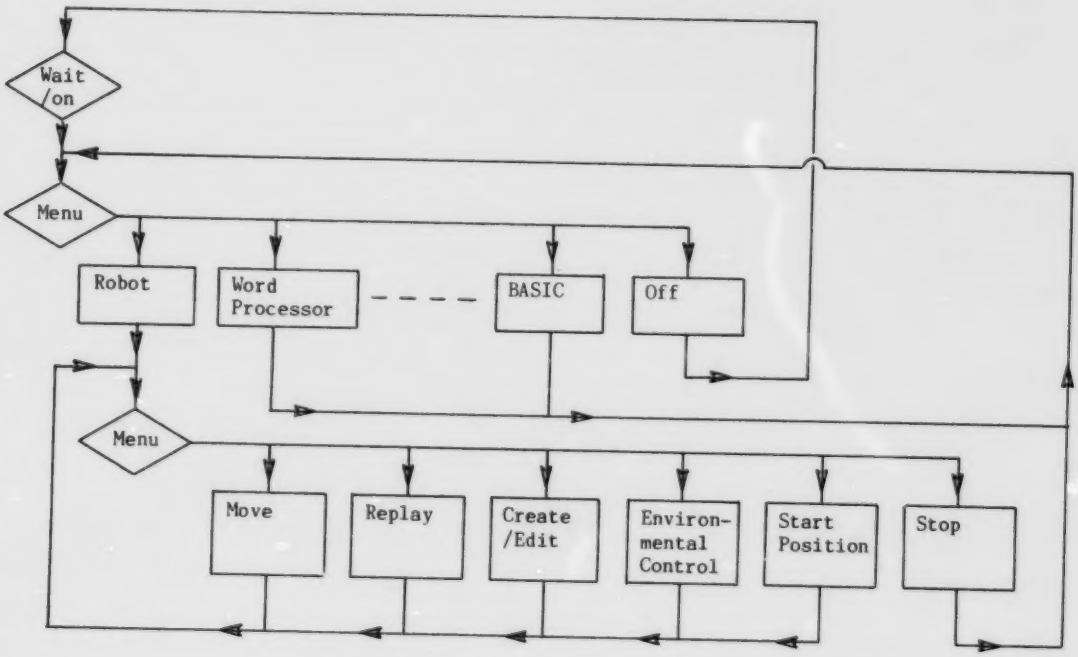


Screen display for robot control.

Fig.4

is not properly centralised. In addition, short routines, such as to pour from a mug may be called with the robot arm in any position. This approach allows the effective use of pre-programmed routines in an environment which is structured, but not precise. This reduces the control effort required from the user while allowing him to retain full control over the robot.

It is intended that the computer will also be available to the user for applications such as wordprocessing and BASIC programs, using a mouthstick. The flow of control is as illustrated in Fig. 5.



Control Flow Diagram.

Fig.5

A limitation is that it is not possible to use the robot from within any of the applications. Therefore if the robot is to be used for manipulating discs this must be done before the application program is entered.

The workstation will be placed for trials at the Duke of Cornwall Spinal Injuries Unit at Odstock Hospital, Salisbury as well as being taken to people's homes. Following the trials it is intended that a purpose built manipulator will be constructed from experience gained with the Atlas arm. It is intended that further work will be done on the gripper, including various sensors which will be integrated with the user control input. It is also intended that in the final system a dedicated microprocessor will be used, rather than using a microcomputer.

5. STATUS

The feasibility study has been succesfully completed and the construction of the workstation is well underway. It is hoped that the workstation will be placed at the Spinal Injuries Unit for trials over the summer.

6. RESULTS

The system developed for the feasibility study was taken to five disabled users for trials. The subjects were aged between 40 and 65, four men and one woman. Two had high spinal lesions, and three had Multiple Sclerosis. Two were in hospital, while the other three were at home, one of whom did not have a full time carer.

The users were introduced to the robot through simple pick up and move operations, progressing to more useful tasks which could potentially give them greater independence. Drinking was achieved using an ordinary mug, though some users preferred to use a straw, using the robot to bring the mug to a convenient position. The feeding of hot soup from a bowl was succesfully achieved using a modified spoon. The robot has also been used in the laboratory to successfully prepare a hot drink, although this was a long and complicated task taking about 30 minutes. This time could be substantially reduced by using proper jigs and pre-programmed routines. One of the major inadequacies of the system was the approach of simply putting a robot on a table and expecting it to perform useful tasks. The use of a workstation approach should overcome this problem.

All the users, including those without any technical background, were able to quickly learn the method of controlling the robot using a two switch input. It was found though that it took a long time to do even simple tasks. To a certain extent this was due to the user being unfamiliar with the controls, but even for an experienced user the speed of selection of a particular movement using a scanning menu is limited. For some of the subjects a more complex input than two switches could have been used, such as a joystick. Much greater use should be made of pre-programmed routines, while allowing the user to interact with the routine when necessary.

These conclusions are being incorporated in the current system, as described above.

7. FURTHER RESEARCH

The design and development of a simple, relatively low cost robotic workstation is seen as a useful introduction to the application of a robot to the needs of the disabled. However such a system only scratches the surface of the possible applications of robotic technology to such great needs. Using the background of the work already done, and the close working relationship with the disabled and the caring professions that has been established, the Institute is keen to work on the development of a next generation advanced robotic device. Such a device would need to be mobile, possibly mounted on a wheelchair.

8. INTEREST IN COLLABORATION

In order to realise a commercial product the development needs to be done in collaboration with an industrial partner and promising discussions with a UK based manufacturer have started. Collaboration with the School of Engineering at Bath University is also underway in the design of a robot manipulator for the workstation

and also examining a wheelchair based robot. In the long term, the Institute would welcome collaboration with other researchers, especially in looking at mobile robot systems.

9. REFERENCES

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ROBOTS: OUT OF THE LABS AND INTO THE HOME

T. Jones
UMI Ltd., Surbiton, Surrey, England

Problem Statement

How can robotic equipment be made available for rehabilitation purposes on a cost effective basis? What is the development strategy for moving robotic equipment out of the research labs and into general use by individuals with physical disability.

Approaches to Rehabilitation robotics

Two approaches have been followed to date. The first approach is to design and build robot arms specifically for the disabled whereas the second has been to use existing industrial robots or personal robots modified to suit rehab. An example of the first is the development of a manipulator at John Hopkins University and an example of the latter is the use of the Unimation Puma at Stanford University & the Veterans Administration Hospital at Palo Alto. UMI's low cost RTX robot has been used in a number of institutions for rehab purposes and a summary of its uses to date is given below.

Current Status

The applications of RTX in this field are as follows:

Boeing Computer Services

A voice controlled workstation has been built to enable a quadriplegic programmer to operate independently of others in the production of commercial software. His efficiency has been measured as being 80% of a comparable able-bodied programmer.

Cambridge University

A teaching aid for cerebral palsy children has been produced using RTX to manipulate objects in the environment under the control of a handicapped child. This encourages spatial awareness and introduces three dimensional problem solving.

Swedish Handicapp Institutet

A workstation for arthritics is being built to enable severely arthritic clerks and book-keepers to function in work environments by using RTX as an intelligent reacher.

IRV Holland

An RTX is being used in a factory environment to present parts to a handicapped individual who then carries out visual checks on the components.

Tufts Medical Engineering Centre

CALVIN, a rehab robot language has been developed at Tufts to simplify the programming of robots in rehab environments. This runs on RTX and the Scorbot robots.

CEA (French atomic energy authority)

The MASTER programme follows the earlier Spartacus development (where an industrial manipulator was used with quadriplegics). The intention is to produce a commercially viable workstation and mobile system for the severely handicapped. RTX is being used in this programme.

Miami Jewish Hospital for the Aged

The use of robotics (and RTX in particular) is being studied for use with geriatrics as an aid to daily living.

Metropolitan Centre for High Technology Detroit

The use of RTX as a smart excerciser is being evaluated for use in physiotherapy to enable physiotherapists to supervise a greater number of patients.

The future

The transition from pre-programmed structured workstations and direct control manipulators to hybrid systems using sensors, voice control and artificial intelligence will occur. This will result in greater ease of use and will enable a larger number of disability groups to benefit from this technology.

The development of mobile systems, such as UMI's R Theta, will enable a single robotic device to carry out functions in multiple environments (office, kitchen, bathroom etc). The use of vision, navigation, AI and some structuring of the environment will make this a viable proposition.

With the cost of micro-technology reducing massively each year, the wide use of mobile robots in domestic environments can be anticipated in the next five to ten years.

THE CALL CENTRE SMART WHEELCHAIR

P. D. Nisbet, J.P. Odor,
Communication Aids for Language and Learning Centre,
4 Buccleuch Place,
Department of Education,
University of Edinburgh,
Edinburgh,
Scotland

I.R. Loudon
Bioengineering Centre,
Princess Margaret Rose
Orthopaedic Hospital,
Fairmilehead,
Edinburgh,
Scotland

1. SUMMARY

Physically disabled children who are deprived of independent mobility are affected in many ways: reduced opportunities for play and exploration mean that the child is exposed to fewer stimuli and less experience of control over his or her environment. As a result s/he develops a passive style of interaction with people, playthings and tools. Motivation is badly affected by inability and frustration, and this in turn makes the child less likely to attempt the playful and exploratory activities vital to the development and acquisition of new skills. The result is a circular and damaging process.

Mobility is not therefore seen as an end in itself, but as an activity linked to all aspects of the child's personal development of his or her intellectual, physical, communicative and social activities.

The principle aim of the Smart Wheelchair Project was therefore to design suitable devices to allow disabled children to use their existing cognitive, communicative and physical skills to gain access to mobility, and through these motivating experiences, develop and extend those skills. Thereafter our aim was to explore the effectiveness of these devices in changing a child's pattern of development. A major consideration was the cost of the final product.

Commercially available powered wheelchairs are available with a variety of switch and control options, but it was felt that they did not offer the kind of integrated learning environment with close coupling between communication, exploratory learning and mobility tools needed by severely disabled children. The Smart Wheelchair is an alternative, microprocessor based system built onto a commercially-available powered chair, which allows the user a variety of control techniques and gives some control over the dynamics of the chair. It has a number of sensors which enhance the activities and possibilities for severely disabled children and which protect the user and the user's environment. Each of these facilities is independently selectable by either the user or carer. The goal is to present a consistent human/machine interface over a wide range of power-sharing options between chair and user.

The hardware and software was developed to a point where a basic system could be delivered to a local Special School. The system was then modified and developed further, paralleling the childrens' development of strategies for use, and new learning activities.

2. INTRODUCTION

The CALL Centre is an action research project located in the Department of Education of Edinburgh University, which investigates the application of microtechnology to the needs of disabled people and their carer's, particularly focussing on physical handicap, communication impairment, and computer-based learning. In late 1985 CALL obtained a "Hull Unibuggy" (a switch-operated child's powered carriage) from the Department of Psychology of Hull University in England, and used and evaluated the Unibuggy with a number of CALL clients. The aims of the work as reported in Odor (1), were

" • to assess how switch use, and control concepts gained from classroom computer work, transfer to the control of other technological devices such as the Unibuggy.
• to assess how switch usage, concentration and motivation differ when the learning context is independent mobility rather than computer-generated visual or audio stimulus.
• to give individuals experience of independent mobility, allowing them the exploration of cause and effect, length, and spatial orientation concepts.
• to assess the problems of controlling a mobility aid through a small number of simple inputs, and to investigate alternative input and control strategies. "

The results of these trials were very encouraging, but work was hampered by limitations of the Unibuggy: it was physically too large (with a turning circle of around 3 metres), it had insufficient power to cope with surface irregularities, there was no reverse and the system was implemented in hardware making it slow to modify. A specification was therefore drawn up which proposed the use of an electric wheelchair running under microprocessor control, to provide and extend the flexibility of input and facilities of the Unibuggy, but in a more integrated and reliable manner.

The Bioengineering Centre at Princess Margaret Rose Orthopaedic Hospital in Edinburgh has been involved for many years in the production of specialised control systems for powered wheelchairs. One of the areas where it has proved difficult to provide a satisfactory solution to the control problem is where the basic motor control of the user is insufficiently precise to ensure safe control of the chair. Another area of expertise within the Bioengineering Centre is in the control of prosthetic arms, and it was felt that these techniques (described as "Extended Physiological Proprioception", Simpson (2)), could be applied to the control of wheelchairs to improve upon the current switched or proportional position-sensitive systems. The system was envisaged as being microprocessor-based to allow the required flexibility of design, and to provide a range of inputs, environmental sensors and control over the wheelchair dynamics.

The two Centres had arrived concurrently, albeit independently, at a complementary specification for a mobile, and so it was agreed to collaborate by using the same microcomputer and common hardware and software architecture, to which each group could add the appropriate extensions.

This paper describes the CALL Centre part of the project, which is concerned primarily with the educational and developmental uses of the chair, and the link between mobility and use of communication aids.

3. AREAS OF INTEREST

Based on CALL's experience with the Hull Unibuggy, and the work of Butler (3), Douglas and Ryan (4), Brattgard (5) and others, we identified the following design issues:

Exploration and Early Development

Very young children who are deprived of mobility miss out on a wide variety of experiences, and this adversely affects their development. A vehicle that can be easily controlled and offers some safeguards against accidents will be useful in attempting to replace some of these lost experiences. The level of autonomy of the chair should be variable and appropriate to the skills of different children.

Planning and Problem Solving

Successful movement from place to place requires the development of planning and problem solving skills. The vehicle should allow direct control of movement, with varying degrees of help. At a higher level the vehicle should be usable for game-playing activities and wheelchair dancing. For formal problem solving the chair should be programmable in LOGO like a floor turtle.

Mobility Training

The chair should offer a staged approach to mobility training. The user can initially rely on the safety features and search strategies built into the chair. These may be dropped in a principled fashion as he or she gains greater physical and cognitive skill in controlling the chair.

Assessment

Assessment involves ongoing investigation of physical and intellectual abilities. The Smart Wheelchair should be useful in both assessment and training of users, and in the design of suitable control interfaces for the users. Accordingly the chair must be controllable by a variety of simple switches and proportional controls.

Pre-Communication Skills

In order to use a communication aid, children must learn to use a suitable control interface. The chair should offer the chance of practicing these skills in a stimulating environment and then transferring them to the use of a communication aid. Conversely, it is desirable to allow existing users of communication aids or computers to control the chair, therefore the Smart Wheelchair should accept commands via the industry-standard RS232 communications link. (The chair, having both a scanning selector and a data link, combines the mobility and communication functions. This allows the user to either drive the chair, or communicate using stored messages via the serial link, using common controls).

Play and Socialisation

Being independently mobile is simply good fun: giving a sense of power, control and the ability to be naughty. These are absent from many handicapped childrens' experiences. Valid social goals would be attained if the chair allowed the user to choose who and where to go to, and what to do and say when he or she gets there.

Use in a School Curriculum

Wheelchair activities should be incorporated into and enhance the child's school curriculum. Its features should complement both the classroom activities and those in other departments such as speech therapy and physiotherapy.

Motivation

Development depends on the child considering wheelchair work worthwhile. Autonomous mobility appears to be a powerful motivator compared with more conventional learning activities. The motivation springing from the direct control and feedback which mobility offers should be transferable to other aspects of learning and skill development. (We hope that the chair will allow us to investigate a child's individual motivational style, and to encourage passive children to explore).

4. COURSE OF RESEARCH

The project to date involved the detailed specification and design of the Smart Wheelchair to a stage where it could be evaluated in a real setting (in this case, Westerlea School, a Special School in Edinburgh). At time of writing (May, 1988) the chair has been in use in this school for about six months, and development of the chair and its applications continues.

Wheelchair Design

The Operating Metaphor - A Mobility Toolkit

The diverse range of activities envisaged for the Wheelchair required a correspondingly diverse range of facilities and sub-systems. We took a modular approach to both design and presentation of the system as a whole. Each of the sub-systems had to be definable and understandable by both able and disabled people in terms of operation, effect and selection for use. The variety of tasks to be tackled by the chair also required that each sub-system be able to be combined in almost arbitrary combinations to create a system with predictable and reliable characteristics. The use of a mode-driven design was explored. However, this was found to place too many constraints upon the combination of sub-systems, and therefore a toolkit approach was adopted. One intention is that bespoke electric wheelchairs be provided for those people who have used the prototype Smart Wheelchairs. The toolkit approach allows unwanted tools to be left off the tailored systems, thus cutting costs and time for supply.

The inputs, sensors and processes are presented to the user as independent tools, which may be combined by the user or teacher as required to fit a defined task or activity. For example, a single switch may be operated as a "Go-Button" or "Steerer", while the Proximity detector is a "Look-ahead" or "Rangefinder" tool. There are as few limitations on the combination of tools as we can achieve: the system is essentially modeless.

User Input and Control Tools

The motion of the chair may be controlled directly by means of up to five switches, covering forward and back ("Go Buttons"), left and right ("Steerers"),and stop (the Stop Button). Control may also be achieved via proportional controllers, force-sensitive sensors, or proprioceptive controls (all known as Variable Steerers) The effect on the chair is selectable with Momentary, Timed or Latched tools (Motion tools).

In addition, these inputs may control a Scanner, in the form a matrix of LEDs which are activated in sequence until the desired option is reached, and selected. The scanner may be used to drive the wheelchair, or to pass messages out via the RS232 link (the Talk tool). Such messages form the basis of the Communication Aid and Keyboard Emulation components of the Wheelchair.

Control may also come from an external Communication Aid or computer via an RS232 serial link (the Listen tool).

User tools are selected by simply plugging them in. The system will configure itself and automatically accept data from these tools. It accepts commands in a LOGO-style format, and so may be used as a "sit-on Turtle", thus giving a child immediate and concrete feedback when programming in Logo.

System Tools

Safety features include Bump detectors, plus Proximity detection to give more advance warning of collisions. The user must also be protected against hardware or software faults, and so the system is self-monitoring to some degree. The range of activities that should be available to the user should be as wide and exciting as possible, even if the user has very limited physical capabilities (for example, control over a single switch), so a route or line-following capability is desirable.

The Bump tool detects when the chair has collided with an obstacle, and reverses away from it a little to give the user another chance. The Bump detectors (made by the Bioengineering Centre), are large foam pads with microswitches embedded at strategic intervals. Although the design is simple (we had experimented with more complex designs such as long loop wobble switches and water-filled inner tubes plus pneumatic switches), they nevertheless work extremely well.

The Bump-and-Turn tool reverses and then turns the chair to the right by about 30° whenever it hits an obstacle, thus giving single switch users with no steering skills the ability to explore in a rudimentary fashion.

The Look-ahead tool consists of two Polaroid Ultrasonic transducers mounted on the front corners of the chair, reporting ranges up to 35'. It may not be a good idea to encourage users to collide with obstacles in order to turn, and it might be frightening for some, and so the Look-ahead tool slows the chair down before it hits an obstacle, and guides it away from obstacles and walls. The original design worked well on the bench, but suffered from noise problems when running from the wheelchair batteries: a second system is under development.

The Line-Follower is a set of infra-red transducers which detect a reflective strip stuck on the floor. This is provided to allow single switch users to do something more exciting with their Go Button than simply to go forward all the time. It is also envisaged that a more sophisticated user with a communication system could manually drive to the line and then leave the rest of the journey along the line to the chair. The original optoelectronic system has (however) proved unreliable, and so a second system using an active cable is currently under development. This inductive design exists as a working bench model and will be tested on the chair during the coming summer school vacation.

System tools are user selectable by simply plugging them in, or switching them on. They can also be selected remotely by the system itself in response to the rider's switches, options on the scanning selector, or via the RS232 input.

The philosophy underlying all these features is that they must be useful for the learning activities defined above. The aim is not to design a totally autonomous wheelchair but rather to provide a range of tools that complement the user's skills. For example, the Line Follower might be used to teach the user what path to follow to get from one place to another, or to reduce the fatigue involved, but is not designed to be used as a track to shift people around like parts on a conveyor belt. The expectation is also that these tools will be removed as the user gains experience and skill in using the chair. A totally autonomous vehicle is (in our opinion) of questionable value because it is dehumanising to the user. The most socially effective way of moving for any disabled person who cannot move themselves is to get someone to push them.

Wheelchair Dynamics

For the user to learn to control the chair, it must behave in a reasonably intuitive and predictable manner. For example, if the user tells the chair to go forward, then it should do so, and not slew to one side. Ideally, parameters such as velocity, acceleration and deceleration, and rate of turn must be controlled. However, we are using existing chairs which have poor dynamics. Factors such as weight distribution, wheel castors, tyre pressure, floor surface and camber all effect how the chair moves. A Spoke Counter is used as a Speedometer tool to give feedback about the chair kinematics. If the chair is going to be used as a Logo Turtle, then it must be capable of measuring distance and angle, and so the Spoke Counter also operates as the Odometer tool.

The Watchdog tool is responsible for maintaining a check on the status of the system and shutting off the power if it detects any faults.

Implementation

Wheelchair

The cheapest and most practical method of development (and of subsequent production) was to build the Smart Wheelchair around an existing commercially available electric wheelchair. The CALL Smart Wheelchair is based upon an Everest and Jennings Elite. The system connects to it by emulating the existing proportional Joystick controller. A second system is also implemented on a standard BEC chair, using motors and electronics designed by the Bioengineering Centre.

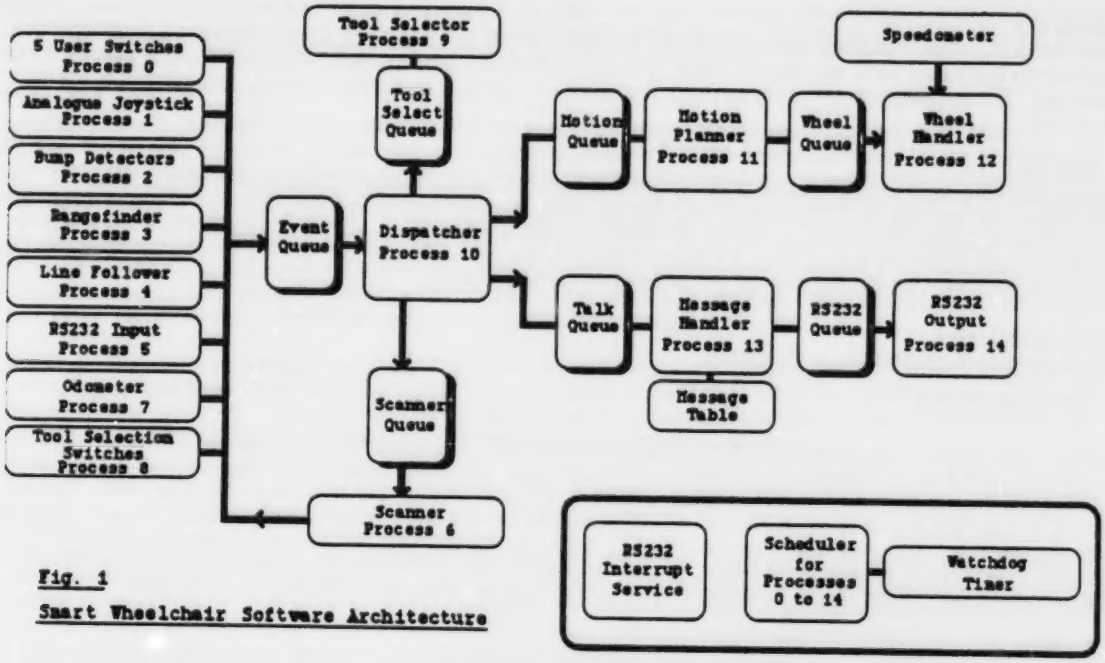
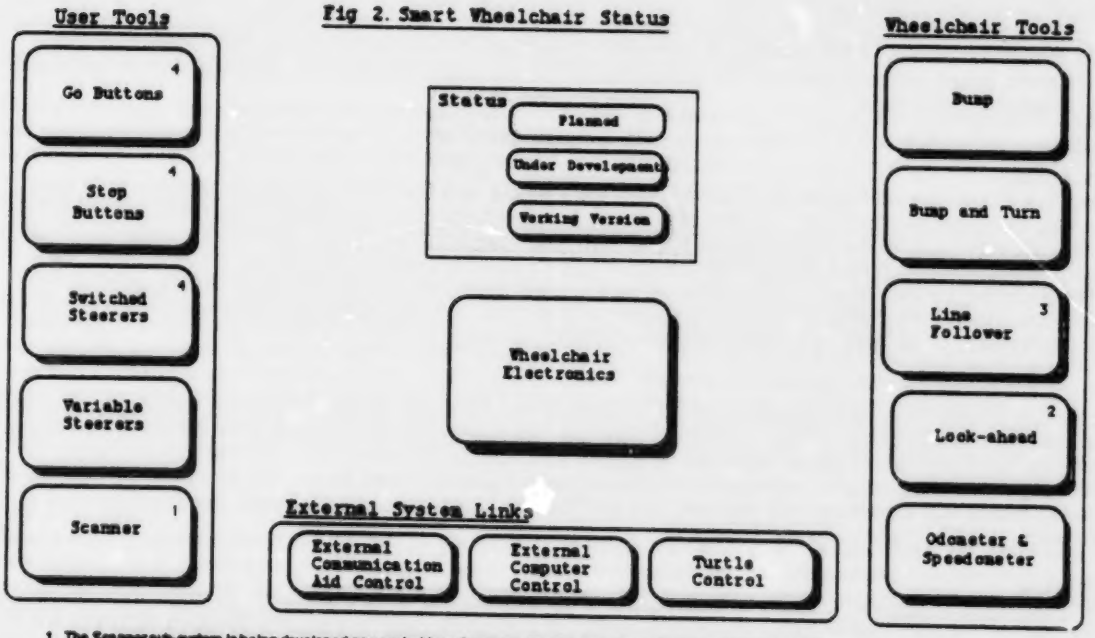


Fig. 1

Smart Wheelchair Software Architecture



1. The Scanner sub-system is being developed as a project by a Computer Studies student on parttime placement in Cail.
2. The Lock-ahead system has been built. The functional design works, but there are power supply noise problems, and the subsystem is being revised prior to installation in the wheelchair.
3. The Optoelectronic Line Follower system proved unreliable, and an alternative system using an active cable has been designed and is awaiting installation.
4. Timed, Latched, and Momentary operations are all available. The development of actual switches, joysticks, or other controls, and their mountings continues.

Hardware
The system is currently implemented in Forth on a Rockwell 65F12 processor with custom-built I/O hardware, connected via separate input and output busses. The RS232 interface supports both XON/XOFF and RTS/CTS protocols. The scanning sub-system is currently implemented on a separate Forth processor, communicating via the Input bus.

Software
System software consists of a number of star-connected autonomous and independent processes or modules, communicating together via FIFO event-driven Queues, (and controlled by a central Dispatcher). We have found this to be a flexible and reliable system that reflects the external presentation of the system. In the absence of a true multi-tasking system, processes are called by a Scheduler on a round-robin basis, and tools are selected by incorporating them into the Scheduler. Fig. 1 gives an overview of the software architecture.

Technical Status
Fig. 2 gives the current status of the system.

5. EVALUATION

The prototype system was delivered to the School in October 1987 . The multidisciplinary school staff were asked to suggest four children of different ages, abilities and backgrounds who might benefit from what we thought the chair had to offer. As there is only one Smart Wheelchair available, only four children are involved in the initial trials. This is mainly so that there is time to create precise and coherent aims for each child against which the chair's characteristics and uses may be tested. We spent two mornings per week in the schools, although the chair was timetabled into the curriculum throughout the rest of the week. Records are kept in diary and video form, and a User Manual (6), Reference Manual (7), and Playbook in which ideas for activities are being written as the trial progresses.

Children
The descriptions and conclusions below are taken from the Diary and the video records. As the trials were not designed to be strictly scientific or psychologically based, the descriptions are informal and are meant to generate discussion.

The first task was to build seating and switching arrangements for each child into the chair. This was a non-trivial activity because of the variation in size of the children (seven years up to seventeen), and involved the creation of mounting brackets and jigs that would allow the child's individually tailored seat (complete with child) to be lifted bodily from his or her manual chair into the Smart Wheelchair. Similarly each child had had some experience of using switches with computers therefore it was desirable to start off by using these same switches to control the wheelchair. The assessment, design and construction of the seating and switch positioning systems was mostly performed by the staff of the Bioengineering Centre.

Terry
Background
Terry is a 17 year old with dyskinetic Cerebral Palsy and dystonia with poor limb and hand control, but good head control. He communicates using a mixture of gesture, poor speech and Bliss (a symbolic communication system), he is intelligent, very sociable and highly motivated in all activities. He has had some experience with a single head-mounted switch and computer software, but has little interest in using a communication or writing aid. Terry has used electric wheelchairs before with no success and so the primary aim with him is to develop his control skills to give him truly independent mobility by the time he leaves the school in June 1988. It is also hoped that Terry will be able to help with the development of the chair by offering comments regarding its design.

Initial Experiences
In his first session Terry used a single headswitch connected as a Timed Go-Button (ie pressing the switch would move the chair for a timed period), with the Bump and Turn tool. He understood the operation of the switch and the Bump and Turn tool immediately, and used the chair to explore all corners of the room he was in. The activities in the following weeks were designed to phase in switches and control gradually until he was able to control the chair himself. The Go-Button was augmented with first one, then two Steerers, which were initially Timed, but then connected as Momentary, as Terry's head-control improved.

Steering
Terry displayed an impressive ability to learn control of his switches and of the chair itself. During the fourth week, for example, we laid out a slalom course which required him to steer to the right between two obstacles, then turn and steer back through another two. On his first attempt he turned early and hit the obstacle, but learnt immediately that the chair moved back as well as turning.At his second attempt he allowed for this by overshooting slightly. He practised his steering by lining up on people and then running them down, but also showed a lot of maturity by stopping at one point

to let a crowd of people in manual wheelchairs past. This ability was extraordinary because this was the first time he had used more than one switch; had control over direction and how the chair steered; used the Bump rather than the Bump and Turn tool; used Momentary switches; and used the new switch array itself.

Independence

After seven weeks practice, Terry started using his two headswitches as Steerers and a hand squeeze switch as a Go-Button. On his first session with these controls, he practiced outside the school for 15 minutes. With some effort he was then able to guide himself through a door back into the school, down the corridors and into as many of the classrooms as the teachers would allow. The Bump detectors were then disconnected and he used them as bumpers: if he misjudged the angle of approach the bumpers guided the chair through doorways and along walls. The bumpers still occasionally get caught against uneven objects, and so the Look-ahead tool should be useful to Terry when it is completed. By the end of the session he had an impressive ability to cope with the variances of the chair's motion and the limitations of the switches as control tools and he could manoevre himself within fairly tight confines. Terry chose where he wanted to go, and went there under his own steam, and so was truly independently mobile.

Terry's development was physical rather than cognitive: his head control and switching abilities have developed from controlling a single Timed headswitch, to controlling three momentary switches which can be effectively combined to give him five different operations (forward, left, right, forward-left, and forward-right). A cut-down version of the Smart Wheelchair (without the Smarts) is to be supplied for his own individual use.

Nigel

Background

Nigel is a 13 year old boy with Spastic Diplegia, epilepsy and some visual impairment. His speech is mostly intelligible (although the content tends to be repetitive) and he lacks social or interactive skills. His postural control is poor and he tends to slump over to one side. He has good arm control, especially if his hand is grasping and located, but he has little motivation to use his abilities for any purpose. When presented with a switch he tends to batter the switch for the sake of it rather than to control the computer or other device . It is hoped that the chair will give Nigel a meaningful task to perform with his switches and so give him something to actually communicate about. The extent and type of his visual difficulties are unclear and it is hoped that the chair can be used to assess his vision.

Initial Experiences

On his first session Nigel used a single plate switch as a Momentary Go-Button, with Bump and Turn. The momentary action was chosen so that he would have to hold the switch down to get anywhere, because of his battering tendencies. This behaviour diminished rapidly after a few weeks, which indicated that he found his mobility more motivating and absorbing than the computer-based activities which he had previously been doing.

During this first session he quickly became skilled at looking ahead and stopping in front of objects before he hit them, and would sometimes inch forward until he was almost touching. He then discovered that it was more fun to knock the obstacles over, and that the only way to turn was to bump into things, and so he proceeded to do so with gusto.

Exploration versus Direction

After the success of his first attempt, we felt that Nigel could cope with two switches, one connected as a Go-Button and the other as a Right Steerer. The second session was an extremely good example of the kind of approach that is not beneficial when introducing an activity as rich and exciting as mobility. There were many more people involved than the previous week, and we all offered advice and instruction at the same time with the result that he did not have a chance to actually explore and learn for himself. After some discussion we agreed that we would keep in the background on the third session, and the difference in Nigel's performance was notable. In this third week he went back to using a single switch as a Go-Button, and was much more relaxed and in control. We watched him exploring the switch and the chair's motion, and listened to him vocalising in anticipation of, and in response to, movement and collision with obstacles. One particularly impressive piece of control was when he realised that the chair was jammed because the Bump detector was not in contact with the obstacle, so he got a staff member to stand in front so that he could bounce off her and turn round.

Physical skills

Nigel's hand control improved rapidly, and he did move on to using two switches for Go and Steer, and developed quite fine control. He had problems with locating his hand on multiple switches and so a single multi-function switch was introduced (ie a joystick). The joystick was a marvel of sophisticated technology (made out of Lego) which allowed varieties of gating arrangements to be used in a structured manner. The joystick is currently gated to give forward and back, which result in Go and a 180° turn respectively.

Nigel still abuses his switches when using them for anything other than controlling the wheelchair. This is good, because it shows the motivating qualities of mobility, but bad in that he has not as yet transferred his control skills to these other activities. Although his hand function has improved tremendously, it is felt that he needs something that gives better feedback about the action of the joystick. An alternative, which might bypass the problem, is to use a Force-sensitive or Proprioceptive joystick such as is being developed by the Bioengineering Centre.

Motivation

The motivating aspects of mobility have been made apparent in a number of ways. When he was in the chair, Nigel's posture improved so that he did not slump sideways and he demonstrated his vision by recognising people at a distance and telling them that he was coming to get them. On several occasions when we played hide and seek, he could spot people hiding behind tables and chairs, or a hand waving at him from behind a door 10 metres away. He would move towards them, indicating that his vision and reasoning skills were in fact fairly good. The chair allowed him to be bad in some quite sophisticated ways. He constantly has to be persuaded and bribed to stop driving and go into class / therapy / lunch / home / etc. and his favourite trick is to lull us into a false sense of security by driving in the correct direction, and then without warning reverse and try to escape in the opposite direction. He has developed into quite a strong personality when using the chair, as it allows him to dictate games such as hide-and-seek, where he tells people where to hide before going to search for them.

Diane and Ruth

Background

Ruth and Diane are pupils at Westerlea Junior School, and are described here together.

Diane is a severely mentally and physically handicapped, passive, 10 year old child with poor spatial awareness and hand-eye coordination. Goals are to use the chair to motivate Diane to improve the use of her hands and to give her something that she will be successful at in order to boost her confidence. It is also hoped that the independence resulting from her use of the chair will encourage her to express herself and give her more incentive to communicate.

Ruth is an alert, well-adjusted six-year old with severe physical disability due to mixed cerebral palsy. She has poor motor control but had a small amount of experience using a single switch with a computer. Goals for Ruth are to encourage the development of fine motor coordination and skills, and to give experience of mobility, and independence. It is hoped that the opportunity to explore will encourage her to initiate activity and to improve her expressive skills and spatial understanding.

Initial Experiences

We wanted to introduce mobility to Diane and Ruth gently and so, for the first session they sat on a therapist's knee as the chair was driven around. Both appeared to enjoy the experience and therefore they were each given control in the second session. Diane used a lever switch mounted on a wheelchair tray while Ruth used a flush-mounted light action switch which was embedded into another tray. Both were connected as Timed Go-Buttons. We selected the Bump tool rather than the Bump and Turn tool so that we did not worry the children by letting the wheelchair appear to be in control. This meant that the children could not explore their environment as the boys had done, and so the school staff thought up a number of activities that the children could do that were more interesting than simply going forward. These included hide-and-seek, searching for lost items such as Teddy Bears or clothes, acting as the Postperson for the school and visiting each classroom with the post, playing at shopping (using Blisssymbols to communicate the items to be purchased), and mapping out routes round the building with pictorial and Bliss-based stations to be visited at each point. Although the children were not using Steerers, they chose where they wanted to go by indicating the desired direction to us (Diane with a yes-no dialogue, Ruth using Bliss), and then driving themselves once the chair was pointing in the correct direction.

Exploration revisted

After about three months use, we were concerned about the lack of progress that Diane and Ruth were making, compared with the boys in the Senior School. We felt that although they enjoyed using the chair, appeared to understand what was happening, and had developed more expressive language as a result, their physical control did not appear to have improved as fast as the boys'. This may have been because the boys, being older, had greater understanding of the tasks and a higher level of cognitive and physical development, and therefore learnt the new skills required to control the chair faster.

We began to think that we had been too cautious when introducing the chair to the children initially, and that we had concentrated on the classroom activities to the detriment of the basic mobility experience. We therefore started to use the chair in a larger and less cluttered room so that the chair would behave in a more predictable manner and offer the children better cues and more consistent experiences. We stopped directing the children's activity and adopted the same

approach that we had used with the two boys: selecting Bump and Turn and letting Ruth and Diane explore the chair and the environment themselves. We also changed the operation of the switches from Timed to Momentary.

Momentary versus Timed

The experience with Nigel and Terry shows that the child's understanding of the task has a great effect upon physical development: momentary switches give better and more immediate feedback, and allow finer control over the chair's motion, thus giving more feeling of being in control. The school staff report that momentary switches enable them to get a better idea of the younger childrens' understanding of the task. They think that the children have not grasped the basic cause and effect as well as they had originally thought.

6. CONCLUSIONS

1) At the most obvious level, it has been shown to be possible to build robotic systems which share power, even with people of very low abilities. The level at which the person passes control to the machine may be adjusted in line with the person's capabilities as they develop both physically and cognitively.

2) The "toolkit" metaphor offers a powerful technique for describing such systems to the user(s), and for implementing the system. The independence of each tool makes selection and combination to create a system with the desired characteristics straightforward. Each tool must have a defined and consistent behaviour such that the user can recognise the behaviour and the effect it has upon the system as a whole. The use of individual tools,in a system that is composed of other such tools, is therefore easier to predict and learn, for the user, the user's carers, *and the system itself.* This approach is supported in mainstream Robotics and Artificial Intelligence by researchers such as Brooks (8), Morovec (9), and Dennett (10).

3) Independent mobility has proved to be an extremely powerful motivator, and this has side effects in a number of areas - all the children have improved their expressive language abilities and control techniques in a very short space of time. The key to the use of mobility appears to be in the type of activities that are attempted. They should be carefully designed to reflect the skills and goals of each child, and if possible should be of a suitably exploratory nature. The chair offers an extremely powerful resource for observational assessment, because the children's activities are self-directed and exploratory.

4) We feel that the experience of working with the two pairs of children in these two separate ways has shown that the most effective method of learning is to let the user explore, and that it is more important to try to promote understanding and experience of control than it is to provide a physically accessible control technique. The Smart Wheelchair was conceived originally to capitalise upon the motivation that comes from the power, control and fun of being mobile. Anything that diminishes these experiences (such as sitting on the knee of a therapist, or having control over Go but not Stop, or not having any control over direction), will therefore tend to be less effective than activities which include these experiences.

7. FUTURE RESEARCH

1) The first priority is for the completion and testing of the tools that have not yet been evaluated by the users. The second is to build duplicate chairs so that some of the areas that were specified (for example, control via a Communication Aid or a Scanner) may be investigated.

2) The investigation of alternative input mechanisms such as the force-sensitive and active joysticks being developed at the Bioengineering Centre will be continued.

3) A long-term project involving a very young pre-school disabled child would be a suitable research project, as this would enable some of the ideas about development to be investigated more fully.

4) The sensors that are fitted to the chair are relatively crude, and so there could be some mileage in looking at smarter environmental sensors. It should be emphasised however that the object of the exercise is not necessarily to produce an autonomous vehicle. It is conceivable that a user may want the option of being able to issue a single command that results in a complex series of movements from one place to another, but the desire to produce technology for the sake of it should be resisted.

5) The Smart Wheelchair has the ability to operate as a slave system to a more powerful computer (for example, an IBM-compatible laptop), and so the computing power that is available for tasks such as automatic mapping, route planning and following is potentially quite large.

6) Similarly, the use of the chair as a sit-on Turtle for Logo programming is an exciting area of research.

8. ACKNOWLEDGEMENTS

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CLINICAL TESTING OF A LOW COST ROBOTIC ARM FOR THE SEVERELY PHYSICALLY DISABLED

Authors: Markus Fengler, William M. Cameron

Organization: The Neil Squire Foundation
4381 Gallant Avenue
North Vancouver, British Columbia
V7G 1L1 (604) 929-2414

Sponsor: Health and Welfare Canada
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Background Information:

The Neil Squire Robot Arm has been under development since 1983. Much of the initial work on the arm was performed by the Remote Handling Group at TRIUMF, a MESON research facility at the University of British Columbia. Funding for clinical testing was provided by Health and Welfare Canada.

The current arm is a six degree-of-freedom robot. It is powered by 24 volt D.C. motors and is controlled by a digital P.I.D. controller. It is programmed using lead-through-teach. Tasks are recorded and executed using point-to-point translation.

The user interface, which operates on an IBM XT compatible personal computer, is menu-driven. Commands are displayed on the screen and are selected by moving the cursor to the desired command and entering a carriage return. This interface is used to record, edit and play back tasks, move selected joints in real time and move the robot in conjunction with a master/slave control.

The project's goal is to provide the disabled population with an affordable robotic aid.

Problem Statement:

Does the Neil Squire arm effectively provide independence for persons with severe physical disabilities?

Application Area:

This robot is intended to assist the disabled in activities of work and daily living. In a vocational setting, the arm could be used to manipulate objects such as books, paper and computer diskettes. In activities of daily living, the robot could assist in feeding, toiletry and recreational routines.

Research Course:

An extensive survey of existing work, particularly that of Stanford University and John Hopkins University was carried out by G.E. Birch (1). Additional information was obtained through interviews with the disabled and the professionals involved with them.

This information was used to establish the criteria of low cost, ease of use and the capability of performing tasks such as serving a drink, handling books, magazines and manuals, handling computer diskettes, shaving, applying makeup and brushing teeth.

Methods Used:

User attitude, accessibility, system reliability, system performance and duties of the attendant were investigated.

User attitude was investigated through the use of direct questions and standard psychometric tests. The subjects were asked questions relating to how comfortable they felt using computers, what they thought of when they heard the word robot, what their expectations were regarding the robot and what changes they would like made to the system to make it more user friendly.

Accessibility, a measure of how easily the subject can get at the control devices required to operate the system, was evaluated in a rudimentary manner by comparing execution time on certain operations. This was a difficult evaluation because the varied nature of the disabilities and backgrounds of the subjects had a great influence on execution time. It was hoped that the results would define the range and configurations of the input devices one could expect would be used with the system.

Reliability was measured by keeping a log of the breakdowns which occurred during testing.

Performance was evaluated through quantitative data such as time to complete operations and through subjective data from subject responses to questions and comments.

Initially, the role of the attendant was not clearly defined because the level of attendant interaction with the disabled user and the robot depends on factors such as the level of disability of a particular subject and the sophistication of the robot system. Attendants were initially instructed on operation and programming of the robot in workshops. Once they were familiar with the system, they worked with the disabled subjects, helping them operate the system.

A preliminary testing period was carried out in the laboratory in the spring of 1987. Five severely physically disabled subjects were taught how to operate the robot to perform procedures such as moving the robot directly, recording tasks and running tasks. The main purpose of the laboratory trials was to provide guidance in establishing the much larger testing program to be carried out at Pearson Hospital, a long term care facility in Vancouver, British Columbia.

Clinical testing in the hospital started in the fall of 1987. Three different groups were tested: programmers, non-programmers and attendants. The programmer group consisted of eight subjects who were taught how to run, record and edit programmed tasks. Six non-programmers learned only how to run, record and edit programmed tasks. Six non-programmers learned only how to run programmed tasks. Four attendants learned how to run, record and edit programmed tasks and how to set up the system for disabled users.

Status:

Currently, the robot is being rebuilt and preparations are underway for clinical testing in the hospital to resume in late February 1988.

Results:

The preliminary testing in the lab concluded the following:

> "The disabled testers to date have been enthusiastic about the test program and the robot usage and have not felt intimidated by the robot". (2)

"The robot usage was easier to learn than had been anticipated, but the software can be upgraded to be even more user friendly. The tester's body position and the overall set-up were critical to good interaction and each user must be properly assessed and the set-up customized to their use". (2)

Results from the first testing session at Pearson Hospital re-emphasized the conclusions drawn from the results of testing in the laboratory. In addition, it was concluded that: 1, subject anxiety, even when totally unfamiliar with the equipment, was very low; 2, generally, subjects had realistic expectations of the capabilities of a robotic arm, even before exposure to the arm; 3, with regards to accessibility, speed and convenience were very important thus establishing a need for a broader range of faster, easier to use input devices which would suit the range of disabilities that exist; 4, reliability of mechanical and electrical components needed to be improved; 5, some minor changes to joint ranges needed to be made and; 6, the level of interaction of the attendants will always depend on the level of disability of the user.

Further Research:

A proposal to develop an automated office, part of which integrates a version of the robotic arm is presently being submitted to Employment and Immigration Canada. This project will likely encompass the development of a much more sophisticated safety system, as well as expand the user interface.

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THE DEVELOPMENT OF A ROBOTIC AID FOR THE HIGH LEVEL QUADRIPLEGIC: WORK IN PROGRESS

Nicholas Valettas†, Andrew A. Goldenberg†, and Morris Milner‡
†Robotics and Automation Laboratory, Department of Mechanical Engineering
‡Department of Rehabilitation Medicine
University of Toronto

1. INTRODUCTION

Damage to the spinal cord is one of the most devastating forms of traumatic injuries that an individual can sustain. In Canada alone, every year, approximately 1000 new cases of spinal cord injury are recorded. Depending on where along the spinal cord the injury has occurred, the resulting paralysis and loss of sensation below the level of the injury often lead the individual to an existence that is totally dependent on other persons. Furthermore, with the increased life expectancy brought about by the improved medical care and treatment of these patients, it has become of fundamental importance to increase their independence, thereby hastening their return to the community. Not only does this minimize the costs, but, perhaps more importantly, also provides the psychological lift necessary to instill the individual with hope for the future.

In the context of this discussion, independence refers to an individual's decreased dependence on other persons to perform some of the most common and frequent daily tasks. In other words, people who are mentally capable but severely disabled need to control their physical environment independent of continuous assistance from other people (Leifer [1]). Although a variety of technological aids exist to provide environmental control, there currently are no readily available aids that allow the individual to manipulate physical objects in his/her immediate environment. Since patients with C_5 and higher quadriplegia are dependent on others partly because of their lack of prehension, it is obvious that a general purpose device that provides such an ability is necessary. Recent advances in robotics and computer technology make it very tempting to investigate the feasibility of providing such an aid to the physically disabled.

At present, the most common method of improving upper limb function is through the use of orthotic devices. Recently, however, significant interest has developed in the area of Functional Neuromuscular Stimulation (FNS) whereby intramuscular electrodes are used to excite specific muscles. Most often, these are the muscles that allow for prehension (Yamamoto [2]). In parallel with the research on FNS, there has also been a concentrated effort by researchers in Canada, the United States, and Europe to develop a general purpose robotic manipulator to aid the physically disabled (Sachs [3], Harwin [4], Gainor [5]).

When one attempts to recover lost human functions, it is often the interface between man and machine which presents the most difficulties. Normally, control of a robotic arm is achieved by direct inputs to the controller through a standard keyboard. For the handicapped, command of the arm through such a terminal, perhaps by a mouthstick, is limited and speed of control is particularly affected. Recent advances in voice recognition technology, however, offer a relatively efficient and unencumbering mode of control, especially for high level quadriplegics with no residual upper limb motion. It should be noted, however, that controlling a robot through voice recognition does present its own difficulties. In particular, early research efforts have shown that requiring the user to guide the arm through a task by issuing voice commands to directly control the movements of each joint of the robot leads to user fatigue and frustration. The fatigue and frustration result from the high degree of concentration required, especially at the fine motion level, to complete the task (Leifer [6]). It is desirable, therefore, to reduce this "control burden" by increasing the autonomy of the robotic aid. The inherent lack of structure in the robot's intended working environment, however, provides a major roadblock to the development of such an autonomous robotic aid. As a result, most research efforts to date have imposed some structural conformity by adopting a "workstation" approach: the robot is located on a worktable and all objects that it must access are precisely located within its reach (Seamone [7]). The tasks the robot can perform are then stored as pre-programmed routines. This arrangement, by necessity, limits the versatility of the robotic aid. Consequently, some research efforts have, instead, investigated the "direct control" approach where the user remotely manipulates the robot to accomplish a desired task. This strategy resulted in a high control burden being placed on the user, particularly when the user was required to make the fine motions necessary to align the gripper with an object and grasp it.

We believe that the "direct control" approach is the most promising. We realize, however, that for this method to be truly effective, the control burden placed on the user must be reduced. In particular, we believe that providing the robot with automatic grasping capabilities will significantly reduce the control burden on the user thereby increasing his/her acceptance of the system.

2. EXPERIMENTAL DESIGN: Equipment and Methods

The main thrust of the robotic aid project is to investigate the problems associated with controlling the robot, providing it with automatic grasping capabilities, and interfacing it to the user. Furthermore, we have decided to use, wherever possible, off-the-shelf equipment to illustrate the feasibility and viability of such a system for the handicapped. To this end , a commercially available arm and voice recognition unit have been obtained. The robot is the RTX Personal Robot Arm manufactured by Universal Machines Intelligence Inc.. It is a six degree-of-freedom robot that has been marketed by UMI for health-care applications. It features a relatively long reach (68.5 cm) and a large (0.934 m^3) working envelope. It has a vertical travel of 915 mm which allows it to reach objects on the floor as well as objects at table height. Furthermore, it has a 4 kg. lifting capacity which allows it to lift a wide range of objects. High level control of the robot is through an IBM PC/AT compatible computer which communicates with the robot's on-board microprocessors via an RS 232 serial port (Fig. 1).

Three Honeywell ultraminiature infrared proximity sensors will be used to provide the feedback required for an automated grasping algorithm to be developed. Sensors on the robot's grippers can be connected to input/output ports on the robot's microcontrollers through a bank of ten wires in the arm's wiring loom. These wires run from the wrist to the main circuit board where they can be connected to the I/O ports. Two of the sensors will be located at the tips of the gripper's fingers and will point forward to detect objects in front of the gripper. The third sensor will be a "thru-scan" sensor. It will be used to detect objects between the fingers and thus allow for objects to be properly located within the gripper.

The interface through which the user will control the robotic arm is the VOTEK Systems voice recognition unit. This system contains a software package, *Voicekey*™, that allows one to set up a speech recognition vocabulary and overlay application packages with speech recognition. Each vocabulary can have a maximum of 64 words/phrases and up to 100 vocabularies can be memory resident. One vocabulary can be resident on the speech board while the others can be resident in the system memory. In addition, each vocabulary can have "trigger words" that cause the system to activate a different vocabulary. This feature allows one to create a hierarchical command structure which reduces the probability of misrecognition of voice commands. With speech recognition active, therefore, a spoken command is recognized and the corresponding keystroke sequence is passed to the application program. In our case, the application package will be the control software that will allow the user to remotely manipulate the robotic arm.

The main microprocessors on the UMI RTX communicate with the PC according to a communication protocol called IPC: Intelligent Peripherals Communication. To make programming the RTX easier, UMI has provided a library of IPC routines. Each routine uses IPC to perform basic tasks and has a keyword to identify it. These keywords can be included as procedures within Turbo Pascal programs and are used to perform the following group of tasks: i) prepare the arm at the start of operation, ii) define how the arm will move, iii) initiate movement of the arm, iv) query the arm's status, v) stop the arm. There are three modes in which the arm can be moved: manual mode, numeric mode, and interpolation mode. In manual mode, the user initiates motion of the desired joints and the joints keep moving until the user stops them. In numeric mode, the user specifies the desired new position for the arm and then initiates motion of the arm. RTX will then move to this position and stop. Interpolation mode, unlike numeric mode which moves the arm to the new position in the most efficient way, allows the user to specify the path the arm should follow in moving to a new position. In addition to specifying how movement of the arm should be effected, the user is also permitted to specify the control parameters which determine the motion itself. That is, the user can specify the speed and acceleration of the motors, the maximum force that each motor should exert, and the tolerable degree of error associated with the position of the motors. Furthermore, the user has the option of moving the arm in force or position mode. These two modes can be considered subsets of the three main movement modes outlined above. In force mode, the motors apply a constant force to the specific joints being moved. If the arm meets an obstacle and that amount of force cannot move it, the arm stops. On the other hand, in position mode the force increases when the arm meets an obstacle until either the obstacle is moved or the maximum permitted force is reached and the arm stops.

In this project, the user will be required to move the arm to the general vicinity of an object to be grasped and then invoke the automatic grasping routine to grasp the object. Since in most cases the location of an object is not known *a priori*, the user would need to use manual mode to guide the arm to the vicinity of the object. The commands that would be available to the user, through the voice recognition unit, would permit him/her to move the arm in joint coordinates: left, right, up, down, in, out, pitch, yaw, roll, open, and close. Furthermore, the user would also be able to control the speed of, and force applied by, the arm. For instance, three speed and force levels (low, medium, and high) could be provided (Fig. 2).

Once the arm has been brought close to the object the automatic grasping routine (Fig. 3) would be invoked. This routine would drive the arm in interpolation mode so that the path to be followed for scanning the region could be specified. For example, with the gripper open, the arm, would move sideways from right to left until either a signal is received from the sensors or a specified distance has been traveled. If no signal is obtained, the arm would be moved forward an incremental amount and then would travel from left to right. This process would repeat until a signal is received from either of the sensors on the gripper's fingers. If the arm is moving from left to right and a signal is received from the sensor on the left finger, we could conclude that the left finger is at the left edge of the object. The position of the gripper would be marked and the arm would then move in the opposite direction until a signal is obtained from the sensor on the right finger. This signal would locate the right edge of the object. The position would be marked and then the centre would be calculated. A similar strategy would be used to locate the object if the arm was moving from right to left when the signal was received. Conversely, if a signal is received before the region has been scanned (i.e. the object is, initially, inside the gripper's sensing field), the arm would move to the side of the sensor from which the signal was received until the signal is no longer present. This would locate the corresponding edge of the object. This position would be marked and then the arm would continue to move in this direction until a signal is received from the other sensor. This would locate the other edge. Again, the centre would be calculated. Once the centre position has been determined, the arm would move, in numeric mode, to that position. Then, in manual mode, the arm would move forward until a signal is received from the thru-scan sensor. This signal would indicate that the object is within the gripper's fingers and the gripper would close to grasp the object.

3. SCANNING ROUTINE

One of the prerequisites for automatic grasping is the need to specify the target points that define the trajectory the gripper must follow during the scanning phase of the grasping procedure. This trajectory consists of two distinct motions (Figure 4): first, the gripper should move from side to side in a horizontal plane to scan a region directly in front of the jaws. The area of this region is the product of the distance the gripper travels and the scanning distance of the proximity sensor. If an object is not detected, then the gripper should move forward a specified distance in the direction it is pointing and the horizontal scanning motion repeated. Clearly, the forward distance should not exceed the scanning distance of the sensor.

3.1. Horizontal Motion

Figure 5(a) illustrates a typical path the gripper would follow to move horizontally. If we define a unit vector $\vec{u}_h$ in the direction of the desired path, then we can express the position vector, $\vec{p}_h$, of the gripper's target position (x_2, y_2) with respect to the gripper's current position (x_1, y_1) as

$$\vec{p}_h = k_h \vec{u}_h \tag{3.1.1}$$

where k_h is a given constant whose value determines the magnitude of the position vector (i.e. k_h represents half the horizontal distance the gripper will travel). From Figure 5(a), the unit vector, $\vec{u}_h$, can be expressed with respect to the shoulder coordinate frame (X_s, Y_s) as:

$$a_h = \begin{bmatrix} \sin(\theta_g) \\ \cos(\theta_g) \end{bmatrix} \tag{3.1.2}$$

where $-160^\circ < \theta_g < 200^\circ$ and θ_g has a negative sense when measured as shown in the figure. It should be noted that $\vec{u}_h$ is independent of the quadrant the gripper is in and always points to the left of the gripper. Based on this definition, equation (3.1.1) can be rewritten, in component form, as follows:

$$\begin{bmatrix} x_2 \\ y_2 \end{bmatrix} = \begin{bmatrix} x_1 + k_h \sin(\theta_g) \\ y_1 + k_h \cos(\theta_g) \end{bmatrix}. \tag{3.1.3}$$

By extension, then, a third point can also be specified:

$$\begin{bmatrix} x_3 \\ y_3 \end{bmatrix} = \begin{bmatrix} x_2 - 2k_h \sin(\theta_g) \\ y_2 - 2k_h \cos(\theta_g) \end{bmatrix}. \tag{3.1.4}$$

Equations (3.1.3) and (3.1.4) are used to specify the two endpoints of the gripper's horizontal motion with respect to the shoulder coordinate frame (X_s, Y_s). In developing the algorithm it will also be necessary to identify several intermediate points that lie on the line between the two endpoints. These intermediate points will be used to describe the specific path the gripper is to follow in traveling from one endpoint to the other.

3.2. Forward Motion

We can apply the same analysis, modified to include a third dimension, to determine the target points for the forward motion of the gripper. From Figure 5(b):

$$\vec{p}_f = k_f \vec{u}_f \tag{3.2.1}$$

where, in this case,

$$a_f = \begin{bmatrix} \cos(\phi_p)\cos(\theta_g) \\ -\cos(\phi_p)\sin(\theta_g) \\ \sin(\phi_p) \end{bmatrix}, \tag{3.2.2}$$

and $4^\circ < \phi_p < -98^\circ$. Furthermore, ϕ_p has a negative sense when measured as shown in the figure. Once more we can express the position vector in component form as:

$$\begin{bmatrix} x_n \\ y_n \\ z_n \end{bmatrix} = \begin{bmatrix} x_{n-1} + k_f \cos(\phi_p)\cos(\theta_g) \\ y_{n-1} - k_f \cos(\phi_p)\sin(\theta_g) \\ z_{n-1} + k_f \sin(\phi_p) \end{bmatrix}, \tag{3.2.3}$$

where $(x_{n-1}, y_{n-1}, z_{n-1})$ and (x_n, y_n, z_n) are defined in Figure 5(b).

4. KINEMATIC ANALYSIS OF U.M.I. RTX

The scanning routine requires that both the forward and inverse kinematic relations for the manipulator be developed. Traditionally, this involves algebraic relationships using coordinate transformation matrices which are derived and used to map coordinates in joint space to coordinates in task space and vice versa. The physical design of the RTX lends itself to a geometric solution of the kinematics which avoids the need for transformation matrices. Such a solution is considerably less

complex and computationally more efficient, and, hence, will be adopted here. It should be noted that a complete solution will not be presented insofar as the wrist roll will be neglected. The basis for this approach is that in this project the manipulator will be required to grasp only objects that have a longitudinal axis normal to the horizontal plane. As a result, wrist roll becomes an extraneous degree of freedom and can be excluded from the kinematic analysis.

4.1. Forward Kinematics

A geometric solution to the forward kinematics involves decomposing the spatial geometry of the arm into planar sections and using plane geometry to obtain the relations that map the joint space coordinates $(\theta_s,\theta_e,\theta_y,\phi_p,z_s)$ to the task space coordinates $(x_g,y_g,z_g,\theta_g,\phi_p)$. For the RTX, the shoulder linkage and the forearm linkage always lie in horizontal planes while the gripper can be at an angle ϕ_p (the pitch angle) to the horizontal plane. From Figure 5(c), the vector, from the base of the shoulder to the fingertips of the gripper, projected onto the (X_s,Y_s) plane, can be expressed as

$$\mathbf{R}_g = \mathbf{R}_w + \mathbf{G} \tag{4.1.1}$$

where G is the projection of the gripper approach vector, E, onto the (X_s,Y_s) plane. By resolving these vectors into their components, we can obtain the x- and y-coordinates of the gripper:

$$\begin{bmatrix} x_g \\ y_g \end{bmatrix} = \begin{bmatrix} |\mathbf{R}_w| \sin(\theta_w) + |\mathbf{E}|\,|\cos(\phi_p)|\cos(\theta_g) \\ |\mathbf{R}_w| \cos(\theta_w) - |\mathbf{E}|\,|\cos(\phi_p)|\sin(\theta_g) \end{bmatrix}. \tag{4.1.2}$$

The magnitude of $\mathbf{R}_w$ is given by the cosine law:

$$|\mathbf{R}_w|^2 = 2L^2 - 2L^2\cos(\alpha), \tag{4.1.3}$$

where α and L are shown in Figure 5(c) and $29^\circ < \alpha < 360^\circ$.
However, by applying the double-angle formula

$$\cos(\alpha) = 2\cos^2(\frac{\alpha}{2}) - 1, \tag{4.1.4}$$

we can rewrite equation (4.1.3) as

$$|\mathbf{R}_w| = \sqrt{4L^2[1-\cos^2(\frac{\alpha}{2})]} = 2L\sin(\frac{\alpha}{2}). \tag{4.1.5}$$

Since

$$\frac{\alpha}{2} = 90 - \frac{\theta_e}{2}, \tag{4.1.6}$$

equation (4.1.5) becomes,

$$|\mathbf{R}_w| = 2L\cos(\frac{\theta_e}{2}). \tag{4.1.7}$$

The angle of $\mathbf{R}_w$ with respect to the Y_s axis is given by

$$\theta_w = 90 - \theta_s - \frac{\theta_e}{2}. \tag{4.1.8}$$

In addition, the magnitude of E is simply the distance from the wrist joint to the end of the gripper and the angle of E with respect to the X_w axis is given by:

$$\theta_g = -(\theta_s + \theta_e + \theta_y). \tag{4.1.9}$$

where θ_s, θ_e, and θ_y are the shoulder, elbow and yaw angles and are shown in Figures 5(a) and 5(c). It should be noted that equation (4.1.9) is independent of the quadrant the gripper is in. Finally, the z position of the gripper is given by

$$z_g = z_s + z_o + |\mathbf{E}|\sin(\phi_p) \tag{4.1.10}$$

where z_s is the position of the shoulder joint on the RTX's vertical column, and z_e is the elbow offset from the shoulder joint due to the thickness of the links. The origin of the Z, axis is the top of the vertical column and the positive direction is upwards.

4.2. Inverse Kinematics

For the RTX, the inverse kinematic relations can be obtained simply by inverting the forward kinematic relations. From equation (4.1.10):

$$z_s = z_g - z_e - |\mathbf{E}| \sin(\phi_p) \tag{4.2.1}$$

Similarly, from Figure 5(c), the wrist coordinates are:

$$\begin{bmatrix} x_w \\ y_w \end{bmatrix} = \begin{bmatrix} x_g - |\mathbf{E}| \cos(\phi_p) \cos(\theta_g) \\ y_g + |\mathbf{E}| \cos(\phi_p) \sin(\theta_g) \end{bmatrix}. \tag{4.2.2}$$

By definition,

$$|\mathbf{R}_w| = \sqrt{x_w^2 + y_w^2} \text{ and } \theta_w = \tan^{-1}\left[\frac{x_w}{y_w}\right]. \tag{4.2.3}$$

Substituting equation (4.2.2) into (4.2.3) gives,

$$|\mathbf{R}_w| = \left[\left[x_g - |\mathbf{E}| \cos(\phi_p) \cos(\theta_g)\right]^2 + \left[y_g + |\mathbf{E}| \cos(\phi_p) \sin(\theta_g)\right]^2\right]^{\frac{1}{2}} \tag{4.2.4}$$

and,

$$\theta_w = \tan^{-1}\left[\frac{x_g - |\mathbf{E}| \cos(\phi_p) \cos(\theta_g)}{y_g + |\mathbf{E}| \cos(\phi_p) \sin(\theta_g)}\right]. \tag{4.2.5}$$

From equation (4.1.7) then,

$$\theta_e = 2\cos^{-1}\left[\frac{|\mathbf{R}_w|}{2L}\right]. \tag{4.2.6}$$

and from equation (4.1.8),

$$\theta_s = 90 - \theta_w - \frac{\theta_e}{2}. \tag{4.2.7}$$

Finally, from equation (4.1.9),

$$\theta_p = -(\theta_e + \theta_s + \theta_g). \tag{4.2.8}$$

A complete solution to the inverse kinematics of the RTX, however, involves more than deriving the relations that map coordinates in Cartesian space to coordinates in joint space. One must also verify that a solution exists and, if it does, whether there are multiple solutions. For a solution to exist, the target point must lie within the manipulator's workspace. Since, in our case, the manipulator will be required to reach the target point by following a specified path, we can verify the existence of a solution by checking whether any of the joint positions fall outside their physical limits. Multiple solutions also present a problem because the system must select one of them. The most reasonable choice is the solution which minimizes the amount that each joint is required to move. These considerations must be accounted for in the inverse kinematics algorithm.

5. STATUS AND FURTHER WORK

At the time of this writing (May 1988), the voice recognition unit has been installed in the PC and the vocabulary created to interface the user to the robot. In creating the vocabulary, we used words that are simple, unambiguous, and meaningful. We have found that short, one word commands are more frequently misrecognized than longer phrases. Moreover, longer phrases better convey the intended function of a command.

Concurrently, we also investigated the effect that varying the sensitivity of the voice recognition unit has on recognition accuracy. When a phrase is spoken, the voice recognition unit compares the voiceprint to a stored template of voiceprints and rates the match on a scale of 0 to 255 with 0 indicating a perfect match. If a match rates lower than the acceptance limit, the phrase is recognized. In our testing, we varied the value of the acceptance limit and found that the unit performed best with a value of forty. At values greater than forty, the unit often misrecognized commands while at values less than forty, the unit did not tolerate the normal variations in speech output. Hence, it often did not recognize commands at all.

Currently, we are in the process of developing the software that will implement the automatic grasping routine. In addition, the proximity sensors will shortly be attached to the gripper and interfaced with the robot's controller. Once the system is fully functional, we will test it in a clinical setting. We have already recruited eight physically disabled individuals to test the system. In selecting these individuals, we restricted ourselves to a group that have been living on their own in the community for some time. Such experience places them in an ideal position to provide constructive criticism of the robotic aid. Furthermore, their apartments will provide ideal testing areas for the robotic aid once the project moves past the laboratory stage.

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7. FIGURES

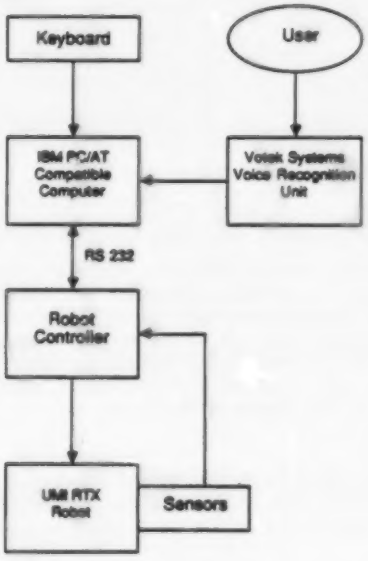

Figure 1: Block Diagram of Robotic Aid System

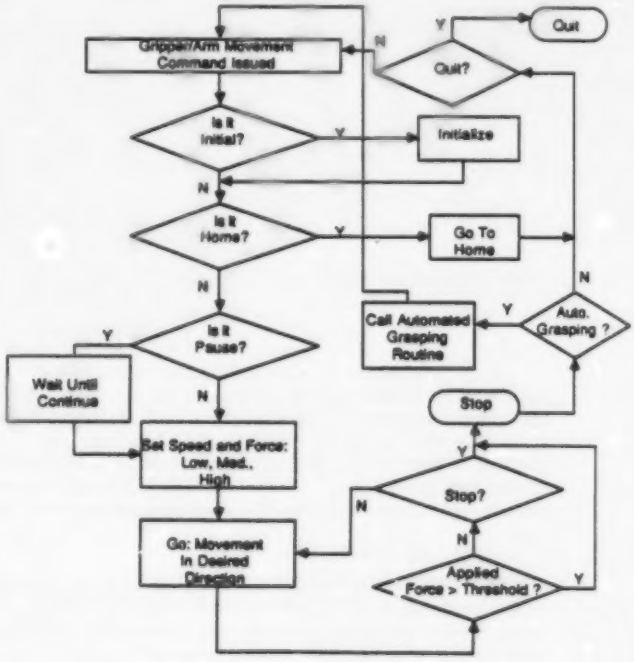

Figure 2: Command Flowchart

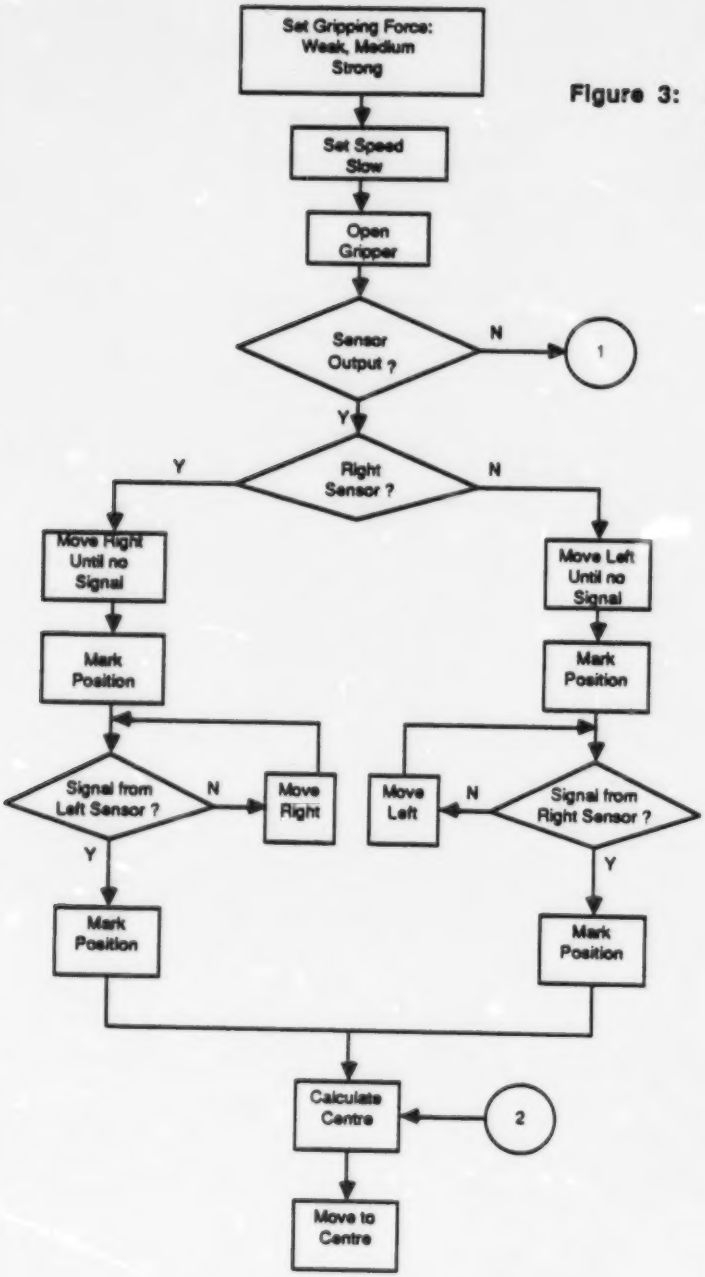

Figure 3: Automated Grasping Routine

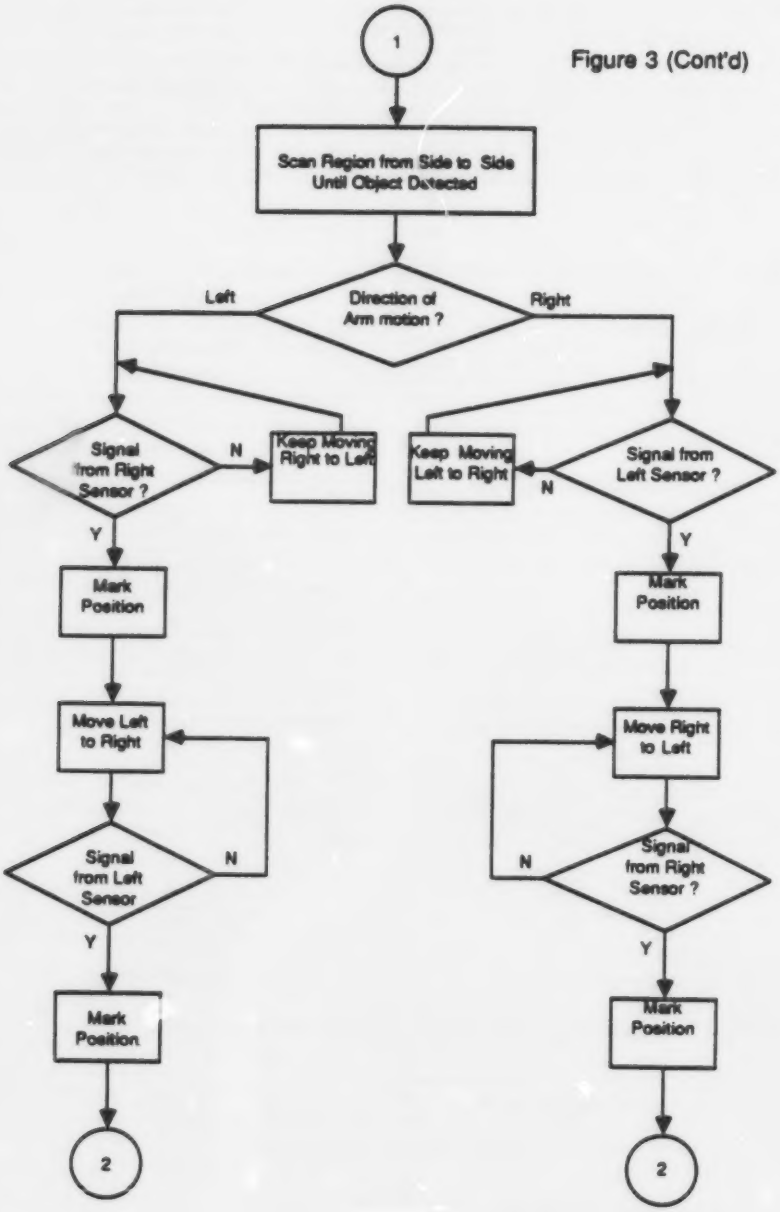

Figure 3 (Cont'd)

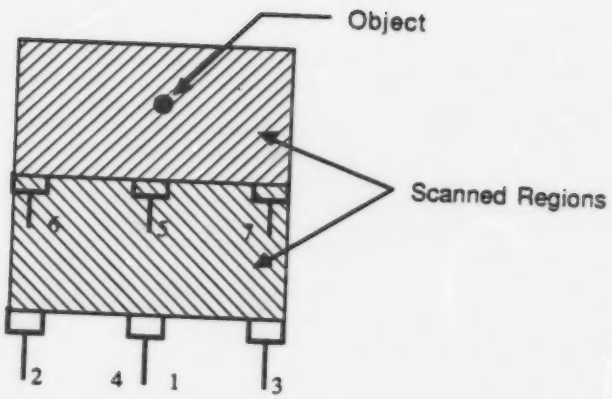

Figure 4 : Positions 1, 2, 3 , and 4 are the locations of the grippper during the horizontal motion of the scanning routine. If no signal is obtained from the sensors, the gripper then moves forward from 4 to 5 and the horizontal motion is repeated.

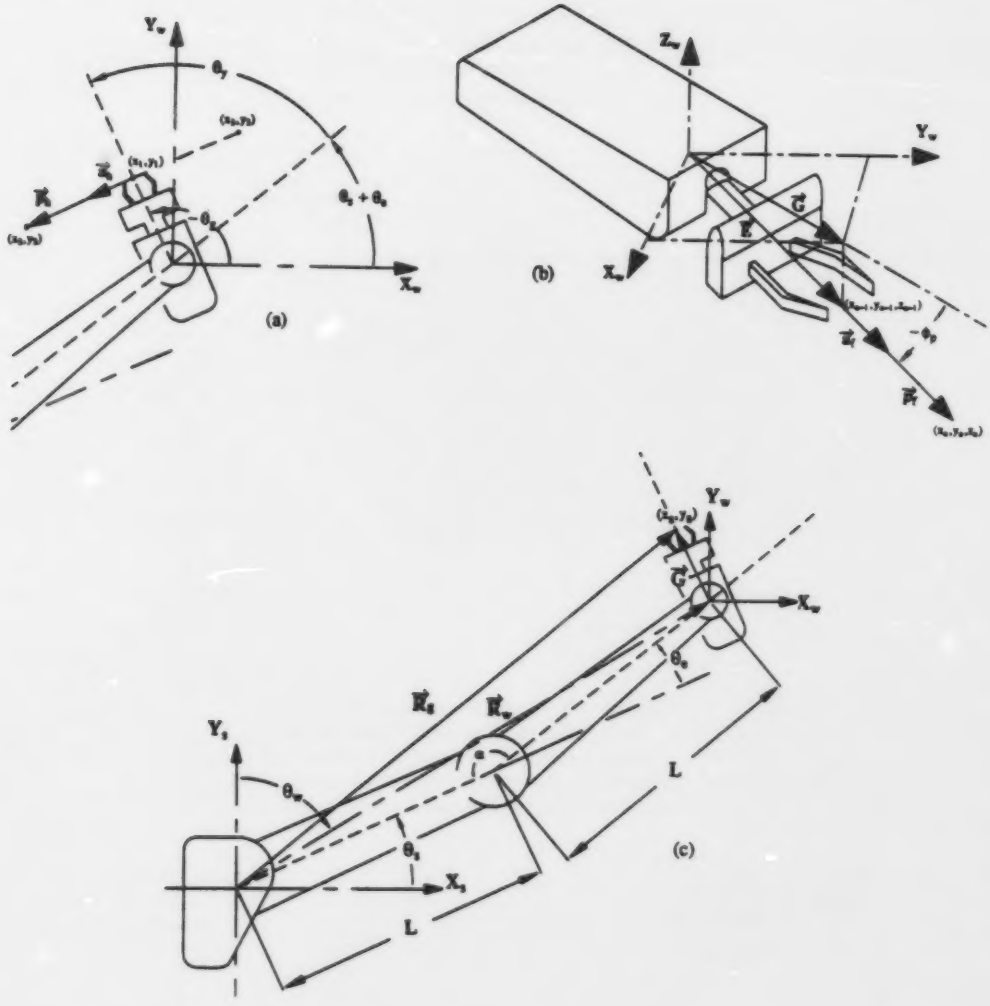

FIGURE 5 Geometry of U.M.I. RTX Manipulator

8. ACKNOWLEDGEMENTS

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ROBOTIC LIMB MANIPULATORS FOR SURGERY

G.F. Auchinleck and J.A. McEwen
Andronic Devices Ltd,
Vancouver General Hospital Research Institute,
Box 58382, Vancouver B.C. Canada V6P 6E4

1. INTRODUCTION

Surgery of the future will involve robotic devices that will position and manipulate tissues, organs, limbs and various surgical effectors during surgical procedures. In combination with advanced patient monitoring techniques, such robotic devices will be able to modify their motions in response to phisiological and morphological parameters derived from the patient, in order to provide the surgeon with greater and more consistent control over the outcome of a surgical procedure.

2. BACKGROUND

Since March 1984, Andronic Devices Ltd., a private company based in Vancouver, Canada, has been involved in the development and evaluation of robotic devices for use in selected surgical procedures. The overall goals of this effort are (1) to improve the quality and consistency of surgical procedures, (2) to reduce the unnecessary exposure of surgical staff to hazardous environments, and (3) to control or reduce costs.

The quality and consistency of a surgical procedure can be improved by allowing a surgeon to move precisely to pre-set conditions permitting standardization of a procedure, while stable, consistent positioning of tissues, limbs, or organs can improve visualization of the surgical site. Robotic devices can also relieve the surgeon from tedious and exhausting tasks such as positioning and supporting limbs or other heavy loads.

Exposure to X-ray radiation is an example of a hazard that may be encountered in surgery. In some orthopedic procedures, a surgeon must manually manipulate the patient's limb while viewing the result under an X-ray image intensifier. A robotic device could be used to allow the surgeon to achieve the dasired manipulations by remote control, with no loss of effectiveness. Robotic devices can reduce or control the cost of performing a surgical procedure by eliminating the need for additional personnel in the operating room, or simply by improving the efficiency of the surgical staff so that the surgical procedure can be completed more quickly.

3. OBJECTIVES OF THE ROBOTIC LIMB MANIPULATOR PROJECT

The first application of robotic technology in surgery investigated by Andronic was the manipulation of limbs during surgery. The objective of the robotic limb manipulator project was to study the possibility of applying industrial robotic technology to the manipulation of patients' lower limbs into the various positions required for diagnostic and surgical knee arthroscopies. A secondary objective of project was to develop an advanced medical robot. An advanced medical robot may be defined as a general-purpose machine system, which, like a human, can perform a variety of different diagnostic and therapeutic tasks under conditions that may not be known in advance.

4. SURGICAL ARTHROSCOPY

Arthroscopy allows visual inspection of the interior of a knee or other joint, either for diagnosis or during the performance of corrective surgery. This is done by introducing an optical viewing system and light source into the joint through a small puncture in the overlying tissue. The optical system and light source allow the orthopedic surgeon to view the condition of the joint either directly or through a closed circuit video system. A probe, knife, or other specialized instrument can be introduced into the joint through a second small puncture so that the surgeon can examine, cut away, or remove damaged cartilage, bone or joint tissues.

During arthroscopy of the knee, a surgeon will typically move the patient's leg into a number of different positions in order to bring various parts of the knee joint into clear view in the arthroscope. These positions may include: an elevated position, which allows blood to flow out of the limb before a tourniquet is applied; a "full extension" position, in which the patient's leg held straight and parallel with the operating room table; a "half flex" position in which the knee is partly bent; a "full flex" position in which the knee is bent to an angle of about 90 degrees; and a "figure four" position in which the patient's leg is rotated and the ankle is moved near the knee of the adjacent leg, such that the two legs together form a figure 4 in a horizontal plane. In each of these positions, the surgeon may wish to internally or externally rotate the patient's

foot, apply valgus or varus strain to the knee joint, or slightly change the position of the leg to improve his visualization of the joint.

5. FIRST PROTOTYPE

In the early stages of the limb positioner project, it became clear that the required load capacity, positioning accuracy, speed and workspace geometry for a limb manipulating robot were all quite different from the requirements of a typical industrial application. Industrial applications generally require robots with high speed and high positioning accuracy, but a payload capacity and workspace size that are small in comparison to the weight and size of the robot. In comparison, the robotic limb positioner is required to position loads approximately equal to the weight of the manipulator, through a workspace large in comparison to the size of the manipulator, but at speeds and with an accuracy much less than that required of a typical industrial application. For these reasons, an approach based on adapting an existing industrial manipulator for use as a limb positioner was quickly abandoned.

The first prototype robotic limb manipulator was a six degree of freedom, pneumatically powered, revolute geometry arm. Control of the limb manipulator was achieved through a combination of a voice recognition system that allowed the surgeon to request various manipulator functions verbally, and keyboard commands entered by an assistant into the computer that operated the manipulator.

The robotic limb manipulator prototype was first used in surgery on March 12, 1985, at the UBC Health Sciences Centre Hospital, in Vancouver, Canada. To the best of our knowledge, this constituted the first use of a robot in orthopedic surgery, and may have constituted the first use of a robot in any type of surgery.

The first prototype of the robotic limb positioner was used in 40 surgical procedures, while various refinements were tested. These clinical trials proved that positioning a patient's limb by robotic means was feasible and offered some advantages over traditional positioning methods.

6. SECOND PROTOTYPE

The second prototype limb manipulator is a seven degree of freedom arm, powered by hydraulics and pneumatics. In order to achieve the advantages of a compliant interface with the patient, the three degrees of freedom of the "wrist" of the manipulator are pneumatically powered. The rest of the manipulator is powered by hydraulic cylinders to provide a strong and rigid positioning base. This combination of a rigid structure for locating the patient's limb in space and a compliant structure for permitting small deviations about that location offers the advantages of both actuation methods.

The actuators used to power the wrist are a new type of proprietary "pneumatic muscle" developed jointly by Andronic and a Japanese company. These actuators totally eliminate "sticktion" effects, and allow the user to adjust the compliance of each degree of freedom powered by the actuators. This feature is used to adjust the performance of the robotic limb manipulator to suit the size and weight of each patient.

The second prototype of the robotic limb manipulator is controlled by an voice control system which is supplemented with a sterile hand control. In use, the surgeon can request any function of the limb manipulator simply by speaking the appropriate command into a microphone attached to his surgical mask. In the event that there is a high level of background noise, or that voice commands are an inappropriate way to indicate the desired motion, the sterile hand control, which is normally clipped to the arthroscope, can be used. Commands originating from either the voice input or the hand control are verbally verified by the voice synthesizer. This combination of features allows the surgeon the option of "hands free" and "eyes free" operation of the limb manipulator.

7. ADVANCED FEATURES OF THE SECOND PROTOTYPE

The second robotic limb manipulator prototype includes features characteristic of an advanced medical robot, in that the manipulator adjusts its operating parameters in response to information derived from each patient. In operation, the length of the patient's lower leg is determined. This information is used by the controlling computer to generate a mathematical model of the patient's leg, from which a safe range of motion for the particular patient is established. The limb model is then used to program five standard positions for the patient's leg, each of which can be recalled by the surgeon. Once the safe workspace is established and the five standard positions are programmed, the controlling computer automatically adjusts the compliance of the pneumatic actuators in the robotic limb manipulator's wrist in response to the patient's weight.

The second prototype robotic limb manipulator has been used in well over 100 surgical procedures to date. These clinical trials have clearly demonstrated that the technical problems of providing the strength, rigidity, range of motion and accuracy of control required for assisting in arthroscopic surgery of the knee have been be solved. It is also clear that the need for a surgical assistant can be eliminated, and that surgical staff can quickly learn how to use the device with no decrease in their efficiency and little change in their existing procedures.

The clinical evaluation of the robotic limb manipulator did, however, indicate several issues that could limit the immediate acceptance of the manipulator system by the medical industry. These concerns related to the perceived cost and complexity of the robotic system, and the difficulty of achieving intuitive control over the robot. Another concern, although not often directly expressed, was discomfort with the idea of allowing the limb manipulator to move the patient's limb under its own power.

8. PRE-ROBOTIC LIMB POSITIONERS

In response to the concerns expressed during the clinical trials of the robotic limb manipulator, the concept of "pre-robotic" limb positioning was developed. The pre-robotic limb positioner is a simple, low cost device, which does not directly move the patient's limb.

Two types of pre-robotic limb positioners have been developed and clinically evaluated. These devices provide a supporting structure that can be manually re-positioned when grasped by the surgeon and will rigidly maintain a new set position when released. One version of the pre-robotic positioner is scaled to suit the range of motion of a patient's arm, while the other is intended for use with a patient's leg. Each device can be adapted to a number of different surgical procedures through the use of interchangeable accessories which grasp the patient's limbs in different ways. We intend to develop advanced accessories for these devices which will offer automated and sensor driven manipulation for specific surgical applications.

9. CONCLUSION

The broad acceptance of robotic manipulation into surgery depends on further development in three critical areas. These three areas can be described as complexity and reliability, intuitive control, and advanced sensing.

The perception of complexity on the part of a user of a new device or system only limits acceptance if there is an associated perception of unreliability or potential for catastrophic failure. A robotic system for surgery must therefore have the appearance of being simple, which can be achieved through an intuitive operator control system, and must also have a high level of reliability and appropriate safety features incorporated into the design. One approach to the reliability and safety issue is to utilize single component failure analysis techniques to insure that any device likely to fail will fail in a way that will not allow the patient or user to come to harm, and in such a way that the failure is obvious to the user.

Truly intuitive control of a robotic limb manipulator would allow an inexperience user to use the device without requiring any training, memorization of commands or switch operations, or other specialized knowledge other than the intended function of the device. A control system that, like a human assistant, could understand voice commands, demonstrations (for example by being led through a particular motion) and would learn from its experience would approach ideal intuitive control. We have attempted to address some aspects of intuitive control with the combination of voice and hand controls, but there is much more development possible in this area.

Sensing of appropriate physiological and morphological parameters, and interpreting these parameters in a meaningful way, remains the single greatest problem limiting the development of advanced medical robots. Sensors that can accurately and non-invasively measure such parameters as tissue pressure, tissue shear forces, forces on a patient's joints, joint positions and many other such parameters must be further developed. Incorporating these parameters into the control algorithms of advanced manipulators will allow the manipulators to achieve a desired effect more directly, rather than by approximation, and in doing so, should offer greatly improved safety and some opportunities for a much more advanced level of control by the user.

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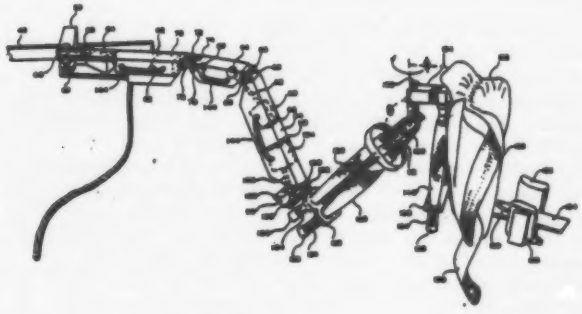

Figure 1: Second prototype of advanced robotic limb manipulator.

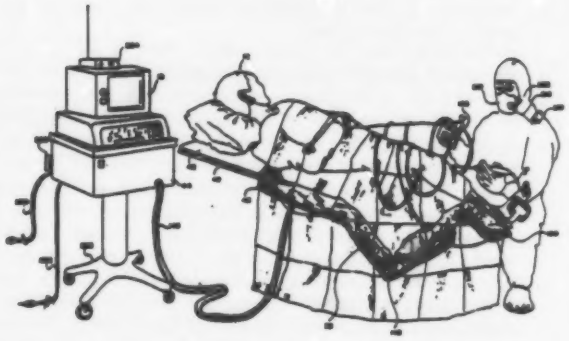

Figure 2: advanced robotic limb manipulator in use.

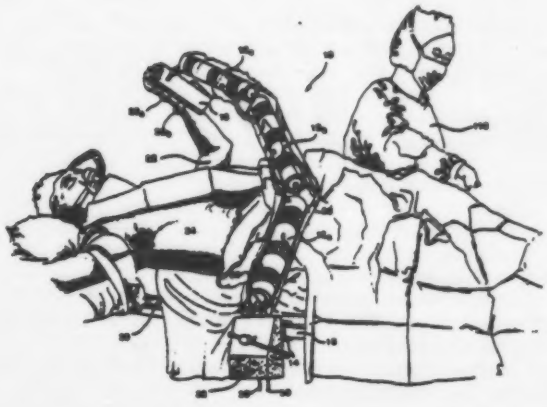

Figure 3: Pre-robotic upper limb positioner.

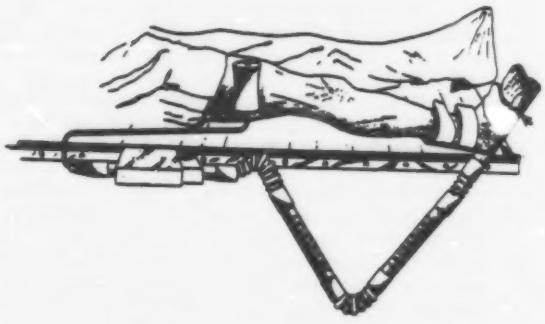

Figure 4: Pre-robotic lower limb Positioner.

THE USE OF A ROBOT IN PROSTATE SURGERY
- A FEASIBILITY STUDY

B.L. Davies*, R.D. Hibberd*, M.J. Coptcoat**, and J.E.A. Wickham***
* Lecturer, Robotics Centre, Imperial College, London
** Lecturer, Institute of Urology, London
*** Director, Institute of Urology, London

ABSTRACT

This paper describes a feasibility study carried out at Imperial College into the use of robot systems as an aid to prostate surgery. As a result of research carried out at the Urological Institute, an advanced cutting and inspection device has been developed as an aid to the removal of part of the prostate gland. The device was mounted in a specially designed linear drive unit and clamped to the end of a 6 axis Puma robot. In a preliminary series of trials, the robot was programmed to execute a series of cutting and sealing strokes to produce an appropriate cavity in a potato. A video of this operation will be shown at the conference.

1.0 Introduction

The words 'Robot Surgeon' may conjure up visions of totally autonomous robots operating on patients with no other human present in the theatre. However, this is far from the intention of the work described here. It is intended that the surgeon will be present, and through the use of additional sensing devices, will monitor the process closely. Then the surgeon can judge whether further cuts are necessary and can override the robot at any time during the process. A surgeon is often required to operate in a very restricted space, whilst avoiding cutting into adjacent vital organs. The posture he is required to adopt can be awkward and tiring. A robot, however, can relieve him of many of these problems. The ability to make repetetive cuts quickly and accurately with a complex trajectory, whilst physically prevented from contact with adjacent organs, makes the robot an extremely attractive proposition for many surgical operations. One such case is the operation to remove the prostate gland.

2.0 The prostate gland operation

In recent years, this operation has been carried out by the use of 'non- invasive' techniques with the aid of a small diathermic loop which is inserted down the centre of the penis. The end of the loop, consisting of a U-shaped piece of wire, is used to burn away small sections of the prostate until the aperture is sufficient to allow the unrestricted flow of urine. The very large number of cuts, combined with the complex conical trajectory of the cutter, makes this a long and tiring operation which takes at least an hour to perform. The necessity to avoid cutting into the urethral sphincter below the prostate gland, further complicates the process. Since this resection operation is now very common, there is a large incentive to reduce the time, skill and stress of performing this operation.

2.1 The ELSA device

In an attempt to improve on traditional cutting techniques, one of the authors (Coptcoat) has undertaken research at the Institute of Urology to develop a new form of cutting instrument called ELSA (Endoscopic Liquidiser and Surgical Aspirator). This consists of a fast rotating cutting blade which is passed down a guide tube containing irrigation and suction channels as well as an endoscope (Fig 1). The ELSA device is used in a 'minimally invasive' technique in which the guide tube containing the endoscope is passed down the centre of the penis. The cutter drive shaft is passed through the guide tube to connect the cutter to the cutter drive so that the cutter, whilst rotating, can reciprocate relative to the guide tube with a stroke equal to the length of the prostate. The cutter is moved by the surgeon through a complex trajectory to remove the excess tissue from the prostate. The surgeon has to take great care to ensure that the cutting stroke is limited so that the adjacent urethral sphincter is not damaged. After a cutting stroke the whole cutter unit can be rotated through 180° to bring a small diathermic loop into position to cauterise and seal the cut. The action of the complete ELSA device is faster and more efficient than the previously used diathermic loop. Nevertheless considerable skill is still required of the surgeon to ensure that the correct trajectory is given to the cutter over a long time period, whilst making clinical judgements based on the view seen through the endoscope. It is very easy for the surgeon to lose his sense of orientation of the cutter within the prostate and it is then necessary to return to the original cutting position to re-establish his sense of orientation. Since the motions are precise and repetetive in nature, it was felt that the process is an ideal task for a robot to both position and orientate the endoscope guide tube, giving the required conical trajectory, and also provide a linear translation of the cutter.

3.0 Selection of a robot system

The ideal form of robot is one designed specifically for the surgical task. This would have a minimum of motion and sufficient hardware and software features to ensure the robot performs only the required motions with 'fail- safe' procedures in the event of any machine failure. However, such safety procedures would make the prototype robot complex and expensive and so it was felt that an initial feasibility study should be carried out using an existing robot which was adapted to the task. Because of the lack of safety features it is not intended that these tests will be carried out on live subjects, but they will be adequate to show the viability of the robot procedures.

3.1 Robot hardware

The robot selected for the task was a 6 axis Unimate 'Puma 560' which was modified by the addition of a drive to provide the cutter with a linear motion whilst also allowing the required changes in orientation. The Puma robot was chosen because it was compact, could carry the required load, and the combination of 6 degree of freedom and the VAL language enabled relatively easy programming of the complex trajectories. A setup was chosen in which the endoscope and guide tube was locked to the 5th (pitch) axis whilst the cutter drive motor was clamped to the 6th (rotation) axis. Thus the endoscope and guide tube could be appropriately positioned and orientated whilst the 6th axis was used to rotate the complete cutter assembly through 180° to allow the diathermic loop to be brought into position to provide a cauterisation stroke. In addition to carrying the cutter assembly, the 6th axis also holds a small DC motor coupled to a linear ball screw to provide the 25 mm stroke length for the reciprocating cutter motion. The endoscope was coupled directly to a small charge coupled camera to allow a view of the cutter and prostate to be shown on a visual display unit. The use of water irrigation and suction tubes ensures that debris can be continuously removed to give a reasonable level of visibility which ensures the surgeon can monitor the process. For the initial feasibility study, tissue with properties similar to that of the human prostate was used. A potato was selected as the most suitable and was clamped into position to model the shape and orientation of the prostate gland.

3.2 The robot software

To allow for even the most enlarged prostate, the robot was programmed to take the first cut down the centre of the gland. The cutter was then moved out radially by a distance of half the cutter diameter and a series of cuts made in a ring around the prostate. Each cut was overlapped with the next to ensure that no large debris particles could be generated, thus minimising a blockage of the debris suction tube. The path of the cut is a curve compounded from the motions of the linear cutter drive and the angular orientation provided by the robot's 5 axes. At the end of each cutting stroke, the 6th axis of the robot is rotated through 180° to bring a diathermic electrode into contact with the cut surface. The current to the electrode is switched on automatically and the robot motion reversed along the trajectory of the cut, thus cauterising the tissue. After each ring of cuts has been made, at the press of a switch the cutter can be moved radially out by half its diameter to initiate the next circle of cuts. This process is then repeated until the desired quantity of gland has been removed. The sequence of cuts is shown in Fig 2. A maximum of 70 cuts is required to complete the operation.

During the whole procedure the surgeon can examine the process using the endoscope and camera and can stop the operation at any time with the press of a button. This causes the current position of the cutter to be registered before moving the cutter to a safe position. The cutter can then automatically return to the interrupted location, or be moved to any other desired position, to resume cutting.

4.0 Conclusions

This initial study has demonstrated the feasbility of the use of robots as an aid to prostate surgery. The time required is about one tenth of those using the current method of a diathermy resectoscope for tissue removal. The robot is capable of giving controlled and repeatable motions with adequate force levels to both carry and move the cutter through the tissue. This relieves the surgeon of much of the physical strain and discomfort inherent in current manual methods. The surgeon has no longer to carry the equipment and provide complex motions of the cutter whilst avoiding adjacent vital organs. This is all carried out by the robot, leaving the surgeon free to supervise the cutting strokes, as displayed on the monitor, without physical distractions. The process can also be interrupted or retraced to a particular cut at any stage of the procedure. This allows the skill and judgement of the surgon to be utilised to the maximum whilst using the robot for routine processes. The prostate removal operation is particularly suited to the use of robot aids because the sequence of cuts can be specified beforehand and the size of prostate does not differ sufficiently to require reprogramming of the robot for different patients. Thus all that is required is that the patient is carefully positioned and oriented with reference to the robot before the start of the operation.

It is now planned to design a robot with only the minimum number of motions and with sufficient hardware and software interlocks and checks to ensure safety. The resulting system could then make the use of a robot, as an aid to the surgical removal of the prostate gland, into a routine procedure.

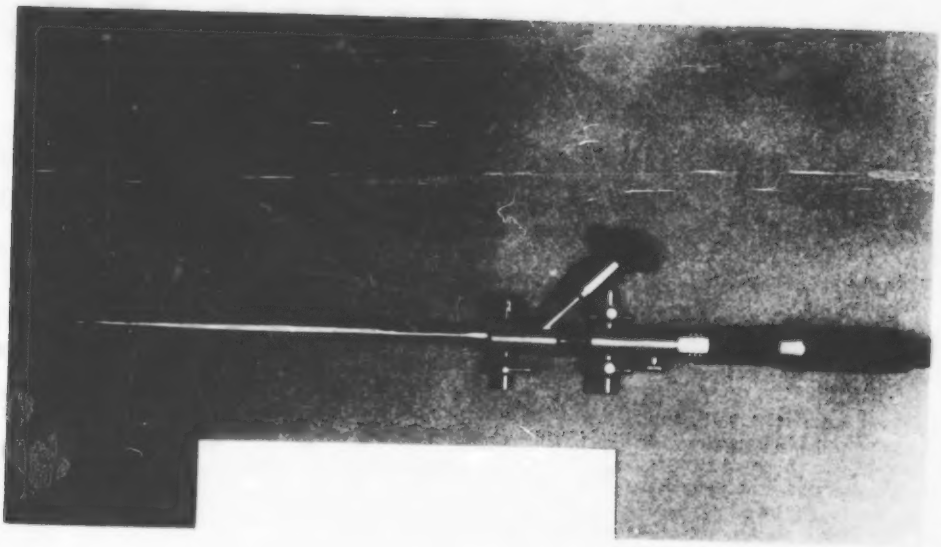

Figure 1. ELSA cutting device.

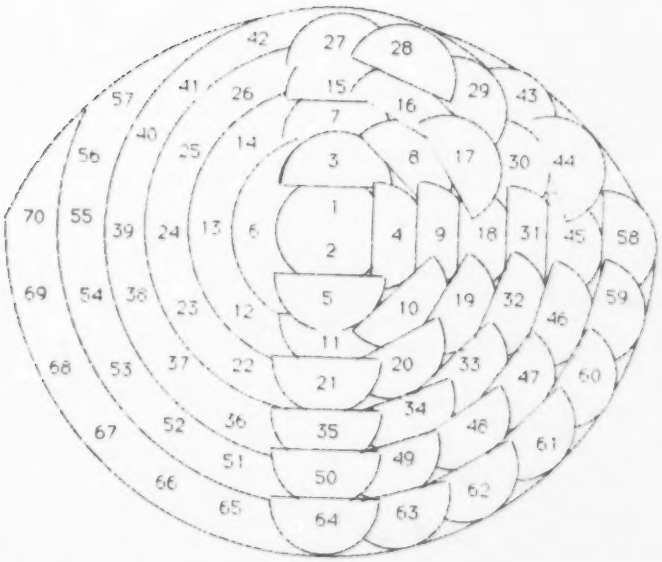

Figure 2. Shape and sequence of cuts at bladder neck.

DESIGN OF A ROBOTIC SYSTEM FOR THE LASER TREATMENT OF ANGIOMAS

W.K. TAYLOR
Department of Electronic & Electrical Engineering
University College London
Torrington Place
London
WC1E,7JE, UK

1. INTRODUCTION

Hand-held blue-green argon lasers are being used (1) to treat angiomas (port wine stains) and, as shown in Figs. 1a andb, significant improvement is possible. Ideally, the potential laser spot should be positioned at the centre of each imaginary square or pixel illustrated in Fig 2 and fired at an optimum dose that is a function of the skin condition at the pixel, ranging from zero for normal skin to maximum permissible at the deeply stained pixel locations. The required accuarcy is difficult to attain over the area with a hand held laser probe and a robotic system is being designed to automatically sense the orientation, distance from skin and position of the probe. By spectral analysis of light reflected from the skin element that could potentially be irradiated by the active laser spot it is also hoped to derive algorithms that will automatically optimise the dosimetry at each spot.

2. LASER PROBE ORIENTATION AND DISTANCE

In general the three dimensional surface equation of the angioma is unknown and the first requirement is that the probe should be automatically maintained perpendicular to the pixel under treatment and at a fixed distance (20mm) from it. This has been achieved to satisfactory accuracy by means of an array of infrared emitters and detectors mounted in the sensing head shown in Fig 3 which has four arms designated N, S, E and W. Outputs from the infrared detectors are processed to derive three error signals that are only zero when the probe is normal to the skin and also at the correct operating distance. The first two error signals drive two motors that control the N-S and E-W tilt of the wrist gimbal orientation mechanism, shown in Fig 4, that also carries the sensing head and the central axis laser probe. The third error signal drives a motor that controls the probe-skin separation.

3. TRAINING METHODS

The wrist mechanism is mounted at the end of a lightweight horizontal link that forms the radius vector of the cylindrical coordinate robot shown in Fig 5. Several methods of training the robot have been considered. Possibly the most tedious method is to have the doctor operate a teach pendant such that points around the 'outlines' of the angioma are stored. As seen in Fig 1a, however, the outlines are not well defined and the patient has to be rigidly fixed to maintain the relative coordinate frames during both the lengthy programming and the treatment. It is envisaged that a simpler method will involve covering the entire stain with a sufficiently large rectangular and flexible pixel matrix, as in Fig 2, and training the robot to scan and store the entire matrix automatically at constant pixel velocity. This would be repeated for the treatment scan without the pixel matrix and with the laser power automatically adjusted by the skin colour algorithm.

4. SAFETY

Safety considerations would prohibit the use of an unmodified powerful industrial robot to carry the laser probe and sensor assembly and numerous safety factors will have to to be introduced. The robot should be physically incapable of exerting more than a specified static force in any direction or of exceeding a specific velocity in any direction. The use of slipping clutches , force, velocity and current sensors together with rigid end stops are possible additions to the skin proximity sensor but considerable experimental work will have to be done before robot laser treatment can be safely introduced.

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(a) Capillary angioma before treatment

(b) Capillary angioma six months after laser treatment

Fig. 1

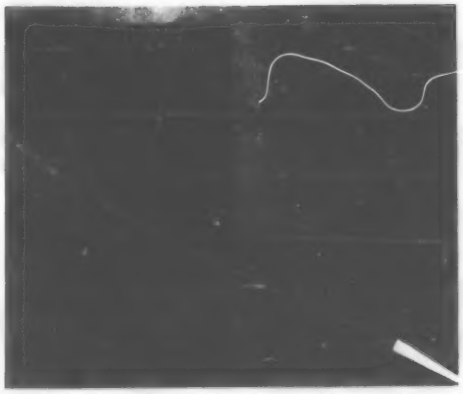

Fig. 2 Robot pixel matrix

Fig. 3 Robot sensing head

Fig.4 Wrist gimbal orientation and distance mechanism

Fig.5 Cylindrical coordinate robot with laser manipulating wrist mechanism

EMG TRAINED, PROSTHETIC CONTROL

George N. Saridis
Electrical, Computer & Systems Engineering Department
Rensselaer Polytechnic Institute
Troy, New York 12180-3590

ABSTRACT

EMG signals generated synergistically on the intact musculature of an upper extremity amputee may be used to train a computer to predict the intended movement of the arm. A probabilistic model is formulated in the feature space of Integral Absolute Value of these signals and pattern recognition is used to classify the various motions. Six single, twelve double and six triple motions of a humerus-elbow-wrist prosthetic arm can thus be generated incrementally and visual feedback may serve to guide the arm to its final destination. The approach requires training of the computer only to set up the individual pattern model of the amputee with minimal mental effort from his past. The procedure has been experimentally verified for the six single motions of the arm.

EMG CONTROL OF A PROSTHETIC OR ORTHOTIC ARM: THEORY AND APPLICATION

In the recent years, many attempts have been made to utilize electric power to operate artificial orthotic or prosthetic arms. Electromyographic (EMG) signals from different parts of the body's intact musculature have been used by various researchers as non-invasive approaches to command and control a battery-powered artificial limb with up to four degrees of freedom [3, 6, 7]. When microcomputers were introduced in the field, they permitted highly sophisticated signal detectors, parameter identification and motion control method. Grapue and his colleagues [1, 2] have successfully implemented a time-series identification method that recovers information from EMG signals from the shoulder muscles of the subject to move a prosthetic or orthotic device. Similar techniques were also developed to successfully generate orthotic locomotion to subjects with spinal injuries.

All the above methods require special training of the subject to learn to generate the appropriate signals to move the prosthesis or orthosis. Saridis and his colleagues [5, 4, 9, 10, 11] have proposed a method for above-the-elbow amputees that utilizes synergistic signals from the intact musculature when the subject makes an effort to move his missing arm and uses them to move incrementally the artificial prosthesis or orthosis. The advantage of this method is that instead of training the subject to generate the appropriate signals for motion control, the computer is trained to understand the various patterns of the synergistic signals, thus giving the burden of training to the computer. Additional information about the speed and direction may be used to make the motion of the arm as natural as possible.

The work by Saridis and his colleagues has been performed in four stages. The first one involved the hardware development and data collection [5]. The second dealt with the EMG signal analysis and classification [4]. The third one treated the modeling aspects and the control algorithms [10]. Finally, the last stage dealt with a microprocessor implementation of the control algorithm and movement of the prosthetic arm. A final stage is still missing where a prototype arm would be fitted and moved by an amputee. All the experimentation was performed on a four degree of freedom, non-portable prosthetic arm, constructed by parts provided by the New York Prosthetic Center of the Veteran's Administration [5], [4]. It can be driven to perform all possible combinations of the following eight primitive motions.

1. Humeral Rotation, In
2. Humeral Rotation, Out
3. Elbow Flexion
4. Elbow Extension

5. Wrist Pronation
6. Wrist Supination
7. Open Fingers
8. Close Fingers

The EMG signals were gathered from skin electrodes, place perpendicularly to the humeral axis and slightly off–center of the bulge of each of the biceps and triceps of the subject with an artificially immobilized right arm. A device called the "Amputation Simulator" was specifically designed for this purpose [5]. Two high gain amplifiers with 5Hz – 1.5 KHz band–widths were used to collect the signals from the biceps and triceps.

Twenty–nine motions and one control (zero) motion were studied in [4]. The two grasp motions were found to generate no synergistic signals on the biceps and triceps and were dropped presently from the study. A thorough statistical analysis based on moments up to the fifth auto–correlations spectral densities and zero crossings was performed with four different subjects which was performed with four different subjects which produced the following conclusions:

1. EMG signals are non–stationary.
2. EMG signals are bandlimited to 1200 Hz.
3. Sufficient pattern information of the arm is contained in the zero crossings and variance of the signals of electrical activity of the muscles.
4. Load and velocity information is also contained in the zero crossing and variance and depends on the integral of muscular activity.
5. Higher moments and auto–correlation do not contain much additional statistical information.
6. In most motions, the variance and zero crossing group in separate clusters, which may be approximated by Gaussian densities identifying different classes of motion.

Using the above results, not only the twenty–nine various motions may be identified and separated by discriminant functions but they may be statistically decomposed to the six primitive motions listed above. For details, see Saridis and Gootee [4].

EXPERIMENTAL RESULTS

After these analytical results had been obtained, a probabilistic model was proposed in terms of the Integral Absolute Value (IAV) of EMG signal activity, by S. Lee and Saridis [10]. This model describes the relation between a signal command and the corresponding pattern in their feature space of IAV of EMG signals [8]. Because of the properties of IAV of EMG, in addition to classification and decomposition to primitives, information about motion velocity and loading was provided. This was experimentally verified when linear movement of the pattern clusters was observed when changes of velocity and load were applied. Details about the probabilistic model, its properties, and use are given in [10]. Once this model was established, a multi–class control algorithm was proposed in the same publication which would classify an IAV of EMG signal to one of the composite classes of motions, decompose to its non–conflicting one, two or three primitives, perform a prediction on the speed and direction of the motion and transmit that to the actuator of the motion and transmit that to the actuator of the prosthesis for implementation of the actual motion. The method has also learning capabilities and an error override for improved performance. Details of the method can be found in reference [10], where mostly simulations using real EMG data verified the feasibility of the algorithm.

From 1983–84, Dr. Hong was able to implement the arm control algorithm on a group of four Texas Instruments TM 990/101M micro–computers at the Robotics and Automation Laboratory of the Department of Electrical, Computer and Systems Engineering at Rensselaer Polytechnic Institute. The whole procedure involves collection of EMG data from the biceps and triceps of the subject who operates from the "Amputation Simulator". From the signals, a probabilistic model of variance and zero crossing patterns in the feature space of IAV of EMG, which describes the relations between commands and motion class. Motion decomposition into six primitives and velocity information is obtained and transmitted to the arm actuator for execution. Figure 2 depicts the various classes for Dr. Hong's experiments with his EMG classifications. A

demonstration of generation of various primitive motions is presented in the accompanying video tape. The arm was moving in intervals of 1.7 secs, according to real–time motion commands generated by Dr. Hong. The results were very interesting, since no training was necessary for the subject. The training of the computer did not take more than six hours total.

Future work should be addressed to the design of a prototype prosthetic arm with fast micro–computers to be fitted on a real, above–the–elbow amputee and have the programs transferred for the final test of the method. It is believed that it will give similar results without any modifications of the algorithms.

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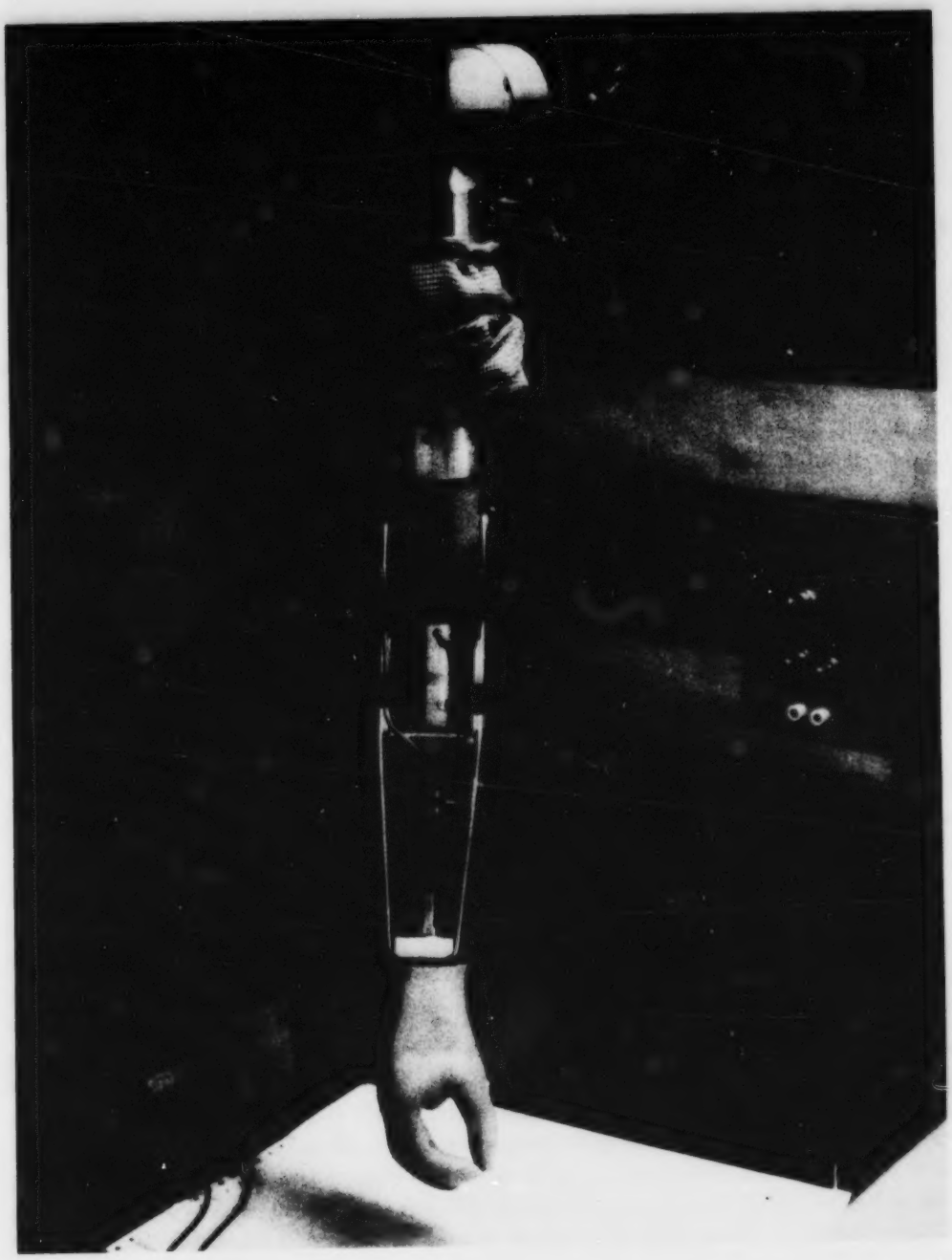

Fig. 1. The Prosthetic Arm

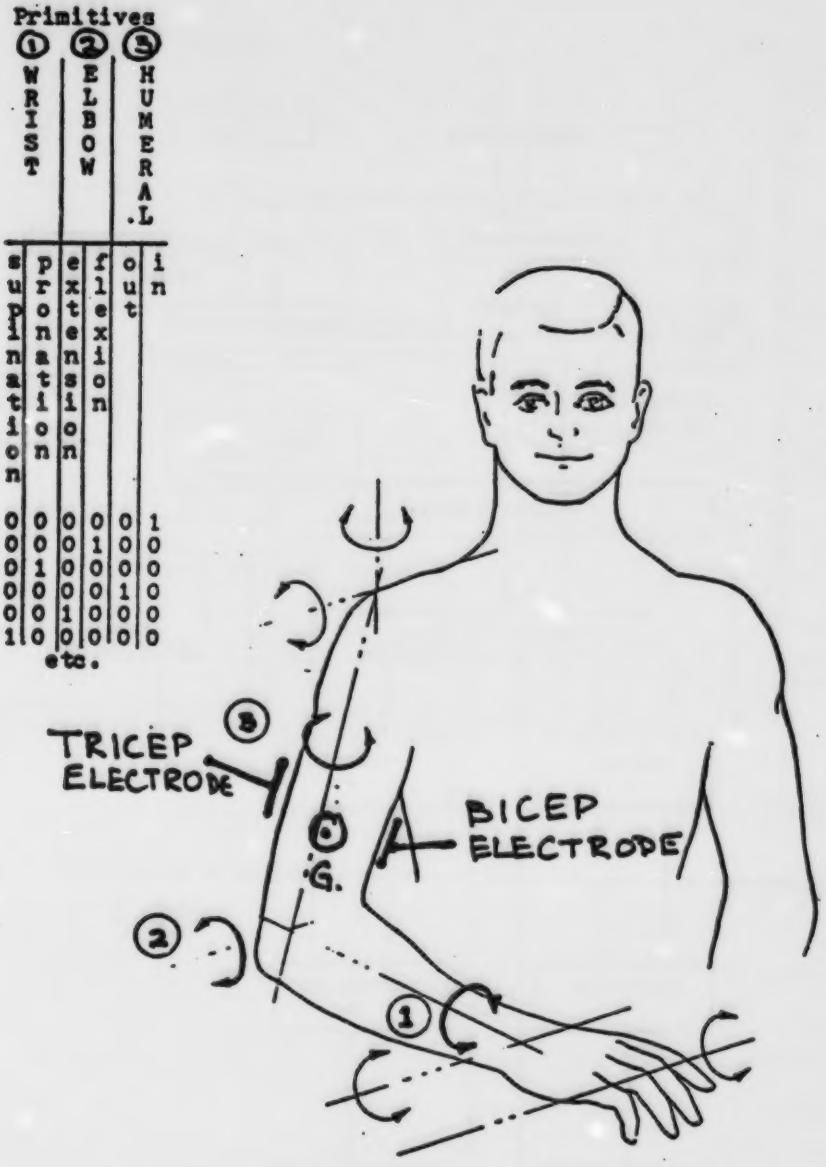

Fig. 2. Code of Primitives

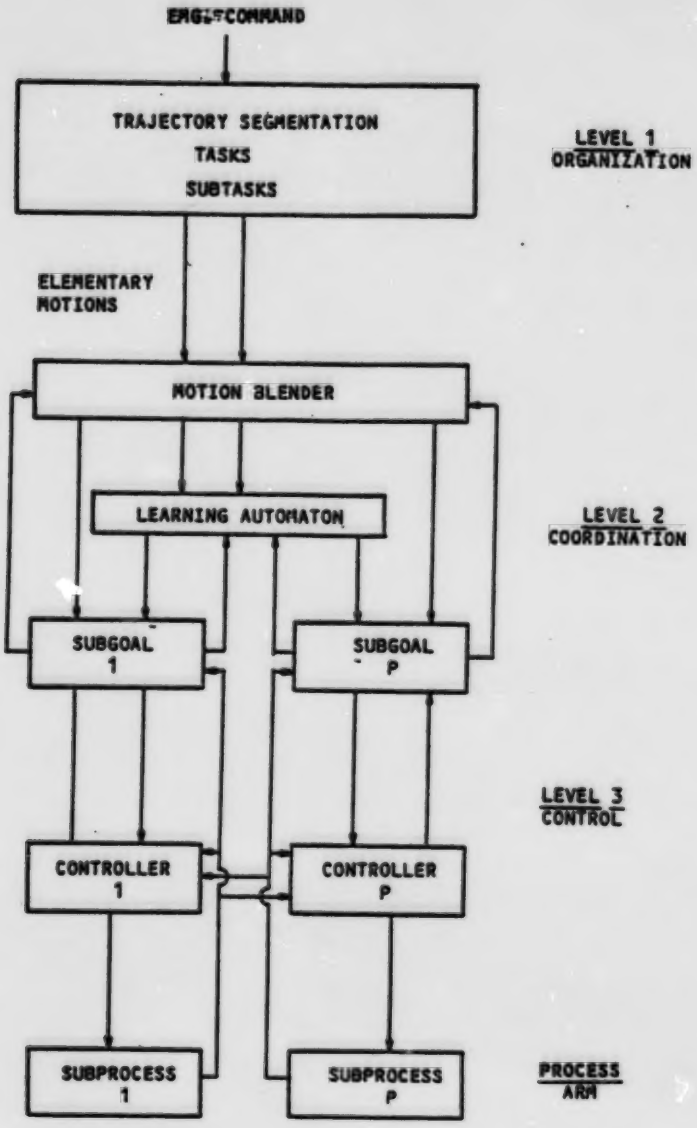

Fig. 3. Hierarchically Intelligent Control of a Prosthetic Arm

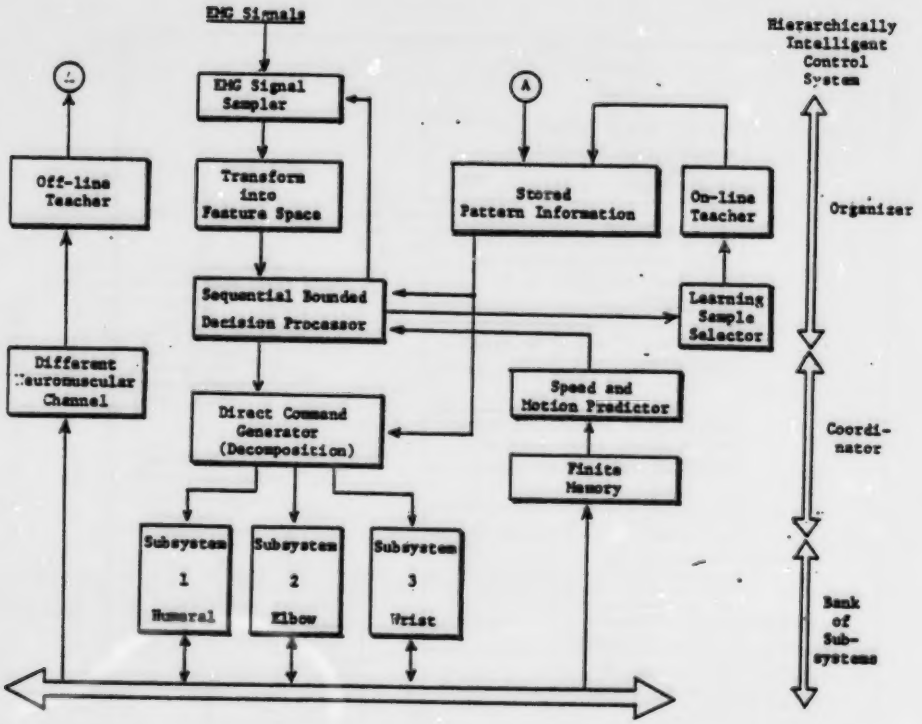

Fig. 4. Block Diagram of the Overall Decision and Control Procedure of the Prosthetic Arm

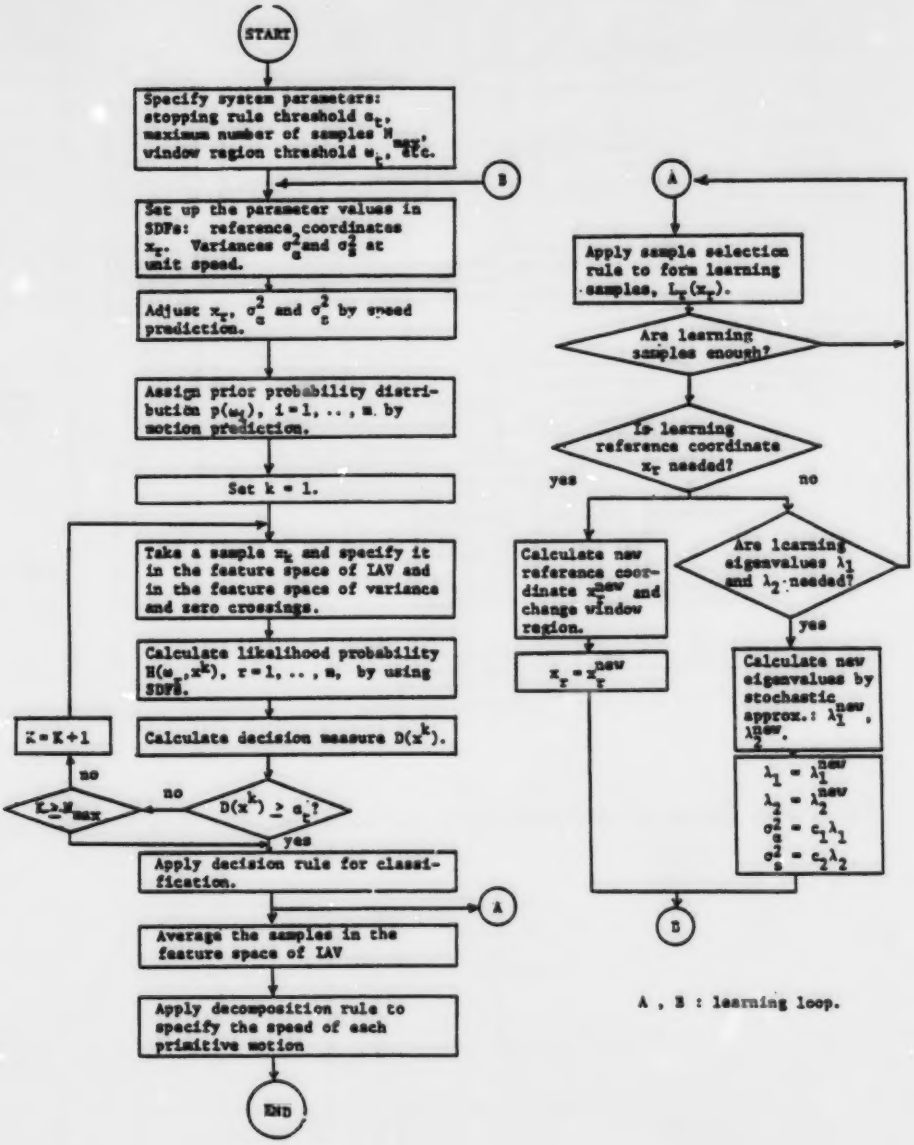
START
Specify system parameters: stopping rule threshold ϵ_t, maximum number of samples N_{max}, window region threshold ϵ_L, etc.
B
Set up the parameter values in SDFs: reference coordinates x_r. Variances σ_a^2 and σ_s^2 at unit speed.
Adjust x_r, σ_a^2 and σ_s^2 by speed prediction.
Assign prior probability distribution $p(\omega_i)$, i = 1, .. , m by motion prediction.
Set k = 1.
Take a sample x_k and specify it in the feature space of IAV and in the feature space of variance and zero crossings.
Calculate likelihood probability $H(\omega_r, x^k)$, r = 1, .. , m, by using SDFs.
Calculate decision measure $D(x^k)$.
$D(x^k) \geq \epsilon_t$?
no
yes
$k \geq N_{max}$
no
k = k+1
Apply decision rule for classification.
A
Average the samples in the feature space of IAV
Apply decomposition rule to specify the speed of each primitive motion
END
A
Apply sample selection rule to form learning samples, $L_r(x_r)$.
Are learning samples enough?
Is learning reference coordinate x_r needed?
yes
no
Calculate new reference coordinate x_r^{new} and change window region.
$x_r = x_r^{new}$
Are learning eigenvalues λ_1 and λ_2 needed?
yes
Calculate new eigenvalues by stochastic approx.: λ_1^{new}, λ_2^{new}.
$\lambda_1 = \lambda_1^{new}$
$\lambda_2 = \lambda_2^{new}$
$\sigma_a^2 = c_1\lambda_1$
$\sigma_s^2 = c_2\lambda_2$
B
A , B : learning loop.

Fig. 5. Flow Chart of Overall Process

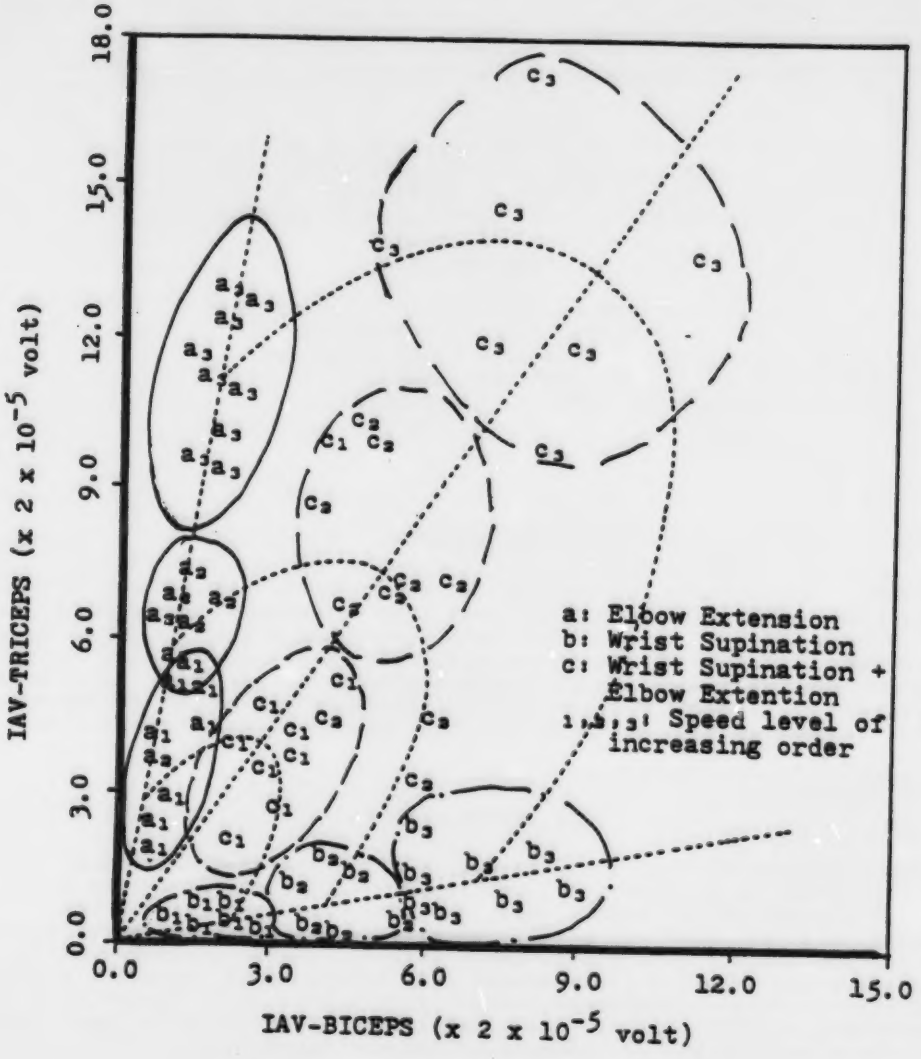

Fig. 6. Influence of Speed of Motion on IAV Clusters

A MULTI-FUNCTIONAL PROSTHESIS EMPLOYING EXTENDED PHYSIOLOGICAL PROPRIOCEPTION AND PROGRAMMED LINKAGES

D. T. Gibbons, M. D. O'Riain* and J. S. Philippe-Auguste
Department of Electrical Engineering
University of Ottawa
770, King Edward Avenue, Ottawa, Ontario
Canada K1N 6N5
(613) 564 2495

* Department of Rehabilitation Engineering
The Rehabilitation Centre
505 Smyth Road, Ottawa, Ontario
Canada K1H 8M2
(613) 737 7350 X580

INTRODUCTION

An artificial device which is used by a person to overcome a disability (whether a pair of spectacles or a prosthetic arm) has to be comfortable to wear, easy to use, reliable and fully under the control of its operator. If the device fails these requirements, it will not be really useful to the disabled person and will likely end up being discarded. We are reporting here the work we have carried out on the design of multifunctional prostheses. In the design of these prostheses, we have ensured that they meet the requirements we have outlined above.

LITERATURE REVIEW

Externally powered upper-extremity prostheses have been in existence since the early years of this century [1]. The first of these prostheses used body movements as control inputs. At that time, this technique was felt to be undesirable and researchers strove towards finding a less visible method of producing the necessary control inputs. When myoelectric control was introduced in the early 1940s [2] it generated high expectations and many believed that the definitive strategy for controlling multi-functional externally powered prostheses had finally been identified. It was confidently predicted that myoelectric control just needed further development before "bionic arms" became a reality. The 60s, 70s and early 80s, witnessed a surge in research on myoelectric control. Early entrants into the field were the Russians [3] who developed a myoelectrically powered hand which was controlled by two sets of myoelectric signals taken from muscles in the stump of the amputated limb. This was soon followed by the development of similar systems in Canada, the United States, Great Britain, and other countries. These early myoelectric prostheses were successful because they involved the single function of grasping. When attempts were made to increase the number of controlled functions, things became a lot more complicated. The initial problems did not deter investigators who thought that optimizing the control strategy would make myoelectric control work. Researchers in the forefront of this work have included Wirta [4], Lyman et al [5], Graupe and Cline [6] and Jacobsen et al [7]. A good observation on the achievements of myoelectric control was given in 1985 by Carlson [8] who pointed out that with the exception of myoelectrically-controlled electric hands, very few powered prostheses are actually fitted. While there are probably many reasons for the poor success rate of such prostheses, it is now clear that one of the major problems (if not the major problem) lies with the control strategy which was totally inadequate.

It was Simpson [9] who best identified the problems with the control of multi-functional prostheses when he showed that the continuing success of body-powered prostheses was due, in a significant measure, to the one-to-one relationship between the input (intact joint position) and the output (position of the prosthesis). The attempt to make the control functions of a prosthesis less visible, has meant that researchers have produced myoelectrically controlled prostheses whose operation is essentially open-loop. A multi-functional open-loop prosthesis will just not work. Early attempts to close the loop by providing electrocutaneous or vibrotactile stimulation have helped very little because such feedback cannot give position proprioception, which is the main feedback parameter lacking in an externally powered prosthesis. Simpson's solution was to use the positions of intact joints as inputs to his prosthesis. Intact joints have their own inherent position proprioception, and this proprioception can be extended to the position in space of the prosthesis, once the amputee learns the relationship. The extension of proprioception from an intact joint to the prosthesis itself was termed by Simpson "extended physiological proprioception (e.p.p.)". So far, no other system has been devised which can give proprioception of the position of a prosthesis to an amputee. Until another method is devised, extended physiological proprioception is the most promising control technique for multi-functional prostheses.

PROPOSED MULTI-FUNCTIONAL PROSTHESIS

We have decided to use the principle of extended physiological proprioception as introduced by Simpson as a feature of our design for a multifunctional prostehsis. The prosthesis that has been studied is an above-elbow prosthesis. This prosthesis has the three functions of elbow flexion-extension, wrist rotation and hand grasp. The intact shoulder joint will provide both the input to the prosthesis and the means of proprioceptive feedback to the amputee. By ensuring a one-to-one relationship between shoulder position and the elbow and wrist joints, the amputee will be able to associate the position of his shoulder with the position in space of the prosthesis.

The input-output relationships and the system dynamics are under microprocessor control. Thus, our system has the advantages both of e.p.p. and microprocessor control. This system was first proposed by us in 1980 [10] [11]. Since then, Doubler and Childress [12], and Carlson [8] have presented systems using both e.p.p. and microprocessor control. However, the control sources and the control philosophy used by these researchers are quite different from ours.

The primary input to the prosthesis in the present study is shoulder flexion-extension. This is the only parameter used to position the prosthesis. Shoulder abduction-adduction is currently not used but could be incorporated at a later stage. A basic constraint of our system is that the only motions permissible with the prosthesis will be those also involving shoulder flexion-extension. Thus, any motion not involving shoulder flexion or extension will be impossible.

Unlike the positioning of the prosthetic hand in space, prehension is controlled by EMG signals from biceps and triceps muscles. The hand grasp is driven by a standard EMG prehension prosthesis system. Sensory feedback of prehension force is not provided in the initial system but could be added later [13].

The use of e.p.p. means that there is a predefined linkage between the position of the intact shoulder and the positions of the elbow and wrist of the prosthesis. This type of predefined linkage can be seen in the use of a Bowden cable to activate a body-powered prosthesis. In such a system, the linkage is fixed in a one-to-one relationship by the mechanical construction of the prosthesis. Such prostheses have proven to be very successful because they are easy to use, reliable and have built-in position proprioception so that the operator does not have to look at the terminal device to know where it is.

In our prosthesis with e.p.p., we are attempting to enhance the system by allowing for more than one linkage. We have overcome the mechanical constraints of the earlier prostheses by using a microcomputer to control the positioning of an electric elbow and an electric wrist. The input to the microcomputer is the shoulder position obtained from a shoulder goniometer. It is possible to store several different linkages in the memory of the microcomputer. Any one linkage may be chosen to suit the task being performed.

TESTING AND RESULTS

We have carried out performance tests on the prosthesis using normal subjects. These tests have been extensively reported [14] [15] and are summarised here. Our main emphasis has been to use e.p.p. to provide closed-loop control of the position of the prosthesis. We designed tests to determine the performance of the prosthesis under both e.p.p. (closed-loop) and open-loop conditions. Comparisons were made between these two operating techniques and also with an intact arm.

For the purpose of the tests, the prosthesis was programmed with a simple linkage where the elbow extends as the shoulder is extended. The elbow was fully extended when the shoulder was about 30 degrees below the horizontal and the elbow was fully flexed when the shoulder was 10 degrees beyond the vertical. Two series of tests were carried out on a group of six normal subjects. One series compared the ability of the intact elbow and the e.p.p. controlled elbow to set an angle. The second series compared the performance of the e.p.p. prosthesis and the prosthesis with open-loop control to perform a spatial positioning task.

The e.p.p. control strategy relies on the ability of the body to associate the angle of an intact joint with those in the prosthesis. Our angle tests were an attempt to see if an e.p.p. type of prosthesis was significantly inferior to the intact arm in setting angles. Our null hypothesis for the tests was therefore that "there is no significant difference between the intact arm and e.p.p. prosthesis in the ability of the body to set angles". For all six subjects tested, we failed to reject the null hypothesis at the 5% level. Thus, the e.p.p. system was not found to be significantly inferior to the intact arm in setting angles.

Our null hypothesis for the tests carried out on the positioning data was that "there is no significant difference between the positioning ability of the open-loop and closed-loop prostheses". The results showed that we are able to reject the null hypothesis in five of the six cases at the 5% level. In fact, we are able to reject the hypothesis at the 0.01% level for these five cases. These five subjects found a marked improvement in the e.p.p. prosthesis over the open-loop model. For the last subject, we are not able to reject the hypothesis at the 5% level and we can say that he was able to control the e.p.p. and open-loop prostheses equally well. This could be seen as an anomally, but should only be seen as such in that his use of the open-loop prosthesis was much better than for any of the other subjects.

CONCLUSIONS

A microcomputer controlled prosthetic arm has been presented which uses preprogrammed linkages to produce coordinated motions of elbow and wrist under the control of shoulder position. We have demonstrated its positioning abilities in a task requiring coordinated movement involving both the prosthesis and the intact shoulder. Also, all six subjects found that they accommodated to the prosthesis very quickly. Thus our results indicate that this prosthesis will prove to be a useful and highly acceptable aid for the disabled.

FURTHER RESEARCH

We are now involved in the study of the ability of the wearer to accommodate to the different linkages available. Each linkage provides a different set of input-output relationships (where shoulder position is the input, with wrist and elbow angles as the output). Hence a thorough study is necessary to determine the ability of the wearer to control the arm using different linkages. This study is underway and is being carried out using simulation techniques to assess the ability of the wearer to learn the different linkages and to use these linkages afterwards. Figure 1 shows a typical diagram displayed on the computer screen obtained from the simulator. The representation of a 3D hand on the computer screen is depicted. The hand moves toward and away from the test subject under the control of the subject's shoulder and in accordance with the linkage chosen. A minimum background is provided so that the subject can judge the movement of the hand in space. Only the hand is displayed as this all that is necessary to assess the performance. The simulator can produce the required video images in real-time. The simulator is capable of simulating the dynamics of any available prosthetic system and of any proposed or even "ideal" system.

Figure 1. Screen display of simulated hand and minimal background.

ACKNOWLEDGEMENTS

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ROBOTICS IN PROSTHETICS

R.N. SCOTT, P.A. PARKER and E. BIDEN
Bio-Engineering Institute
University of New Brunswick
P.O. Box 4400, Fredericton, N,B E3B 5A3, Canada

INTRODUCTION

During the years since the second world war there has been a great deal of progress in the development of powered artificial limbs (prostheses). The achievements have fallen far short of popular expectation, which has been stimulated by TV series and media reports to expect that an artificial limb will perform far better than a normal limb. But the state of the art in powered prosthetics is mildly encouraging.

At this time clinical practice in the best centres in Canada and the USA, the UK and some countries in Europe, offers the unilateral below-elbow amputee a self contained, self suspended prosthesis with an electrically powered "hand" which has good cosmetic qualities and provides a simple prehension function with a maximum force comparable to the normal hand. Control usually is myoelectric, where the electric signal accompanying voluntary contraction of one or more of the muscle remnants in the residual limb provides the control signal.

More complex prostheses, for higher level amputation, are less satisfactory, as are those for bilateral amputees where the absence of tactile as well as proprioceptive feedback becomes a particularly serious limitation. Generally speaking the maximum number of powered functions is three - prehension, wrist rotation (pronation/supination), and elbow flexion/extension. Limiting factors include weight, size, and number of independent control inputs required. But above all, there is a fundamental limit on the number of independent control channels that can be dealt with by the amputee operator, especially when these must be open loop except for visual feedback.

One of the reasons for the development of robotic systems for industrial applications is the inability of the human operator to equal the performance of a machine in reliable performance of complex repetitive tasks. This limitation of the human operator is determined by anatomical and physiological factors. When the human operator is limited further, by paralysis or amputation of one or more limbs, it is reasonable to suggest that robotic aids may come to be considered essential even in the execution of the routine tasks of daily living.

HISTORY OF ROBOTICS IN PROSTHETICS

The development of externally powered artificial limbs, much publicised in recent years, has not involved robot systems to date. Such systems have been used with some success by persons suffering from severe paralysis, [1,2], although this work was many years in development after its initial research in Cleveland, [3]. Until now, even the most complex artificial arm systems have involved individual electromechanical or myoelectric control of each degree of freedom, often on a sequential basis, [4]. In the following sections the reasons for this apparently anomalous development are outlined and the possibilities for future synergistic relations between the fields of robotics and prosthetics are examined.

Reasons for Neglect of Robotics in Prosthetics

The two principal reasons for the 'neglect' of robotics in the development of powered upper extremity prosthetics relate to the state of prosthetics rather than to robotics. These are as follows:

a) until very recently the dynamic performance of available artificial arm systems was so limited that only simple on-off control was justified,

b) until very recently the number of powered functions which could be offered to an arm amputee was so restricted that sequential function was acceptable. Indeed most prostheses still power only a single degree of freedom.

The validity of both of these reasons has been eroded by prosthetics systems development over the past few years, and the future promises further advances which will force the use of robot systems if the full potential of powered prostheses is to be achieved.

Prosthetic Hand Development

The most common application for artificial arms is for amputation of one hand, wrist and distal portion of the forearm - unilateral below elbow amputation. Here replacement of hand function has been considered an adequate objective.

The powered terminal devices now in clinical use have a single degree of freedom - simple prehension. Multifunction artificial hands have been developed in Sweden, [5], and in Japan, [6], but these have not achieved clinical acceptance. A hand featuring a degree of automatic response depending on the shape of an object has been developed in Yugoslavia, [7], and a hand which increased prehensile force automatically to prevent slippage was developed in the USA, [8], but cost and reliability precluded clinical use.

The hands now being used do not provide the user with feedback except that which is available as a consequence of vibrations coupled through the socket. Clinical trials by the authors, [9], indicate a high degree of acceptance of the idea of supplementary feedback of prehension force even in a crude form, but thus far no satisfactory unit has been made available for clinical use.

For some years an alternative powered terminal device has been available from Otto Bock. Called a Greifer, this has a parallel jaw arrangement intended for work situations where the shape and/or soft cover of the "hand" are unsuitable. Interestingly, many workmen have insisted on retaining the prosthetics hand for precisely the tasks for which the Greifer was designed - an illustration of the importance of appearance. A new gripper which may offer more compelling functional advantages is described in the paper by Kemp elsewhere in this session, [10].

More Complex Systems

It is for the less common application, however, that the demand for robotic systems will appear most urgently. For those few persons who have an absence of both arms, or even of one complete arm, the need for a multifunction arm is clear. At this time commercially available systems permit assembling a prosthesis which has three powered degrees of freedom - prehension, rotation at the wrist (pronation/supination) and flexion and extension at the elbow.

Dynamic performance of the modern elbow is such that simple on-off control no longer is appropriate. Thus the need exists for three degree of freedom proportional control. No system available for clinical use will provide this control other than in a sequential mode, and even then the selection of the function to be controlled is far from satisfactory.

Further, there is hope that some additional functions will be powered in the medium term future. Perhaps only a lock/unlock function at the shoulder, together with rotation about the axis of the arm (humeral rotation) will be added initially, but even this will preclude use of available control schemes.

Aside from the need for control of additional functions, there is the need for coordinated simultaneous function in several degrees of freedom. Here there would seem to be no alternative but to utilize robotics techniques. Indeed the developments in robotics are quite timely with respect to the emerging needs in prosthetics.

The observation by Simpson, [11], that a substitute for normal proprioceptive feedback is desirable in multifunction prostheses, becomes even more compelling as mechanical function improves. A comprehensive discussion of this requirement is given elsewhere in this session, [12].

POSSIBILITIES

In considering the possibilities for application of robotics technology in prosthetics certain fundamental constraints must be understood. These are outlined below.

Constraints in Prosthetics

The present state of the art in prosthetics involves attaching the prosthesis to the amputee via a "socket" supported on soft tissue, often with some form of "harness" for suspension and stabilization. Overall weight of a complete arm and shoulder prosthesis for a typical adult amputee should not exceed about 2.5 kg, if full day wearing tolerance is expected. It is very difficult to meet this limit with present prostheses, including the powered actuators and the battery. Any proposal to increase the electromechanical or electronics complexity of the system must address this weight limitation.

Much of the development in prosthetics technology has been directed to means of reducing or eliminating the suspension harness, which was a standard part of earlier prostheses. This is a response to the complaint of many amputees that the harness is uncomfortable, a nuisance in dressing, restrictive of normal movement, and restrictive of choice of clothing. At present most below elbow amputees can be fitted with a prosthesis which requires no suspension harness, some above elbow amputees are fitted without a suspension harness, and the harness for all levels of arm amputation have been minimized. Generally it is not acceptable to add to harness complexity in order to improve control system performance.

All modern prostheses use rechargeable NiCad batteries for energy storage. The usual strategy is to provide sufficient capacity for a normal day's use. Alternatives include batteries which can be replaced readily by the amputee, and provision for "fast charge" of the internal battery. The latter alternative raises important safety considerations however, and may not be accepted in all jurisdictions. For a simple below elbow prosthesis the battery supply is nearly standard internationally, with either five or six 225 mAh NiCad cells - an available energy supply of roughly 5000 watt seconds. Energy efficiency remains a prime requirement for any powered prosthesis.

It is generally agreed that prostheses must be anthropomorphic in shape. This is more than a cosmetic issue. The most important consideration for many amputees is to minimize the degree to which they are conspicuous. Regardless of the functional possibilities of a prosthesis, if it does not offer excellent anthropomorphic appearance it will be rejected. Thus the design constraint of size and shape is very severe, especially in the difficult task of developing powered prostheses for children and small adults.

Finally, the authors would add the constraint that learning to use the prosthesis must not require an extensive training period before rewarding performance is achieved. Undoubtedly for any system the performance will improve with experience, but this will not be achieved if the prosthesis is rejected after a few days because the amputee is discouraged by initial performance.

If the above constraints can be met, there are many possible aspects of robotics technology which may be valuable in prosthetics. A few suggestions follow.

Applications of Robotics Technology

One of the most frustrating aspects of using a completely powered arm and shoulder prosthesis would be the task of controlling six degrees of freedom to position the hand. It is no exaggeration to say that the proposition of controlling such a system via six independent input channels, even if they were available, would be totally unacceptable in clinical practice. Further, unless simultaneous coordinated function of several degrees of freedom is provided, the time required to execute even relatively simple tasks would be prohibitive.

The concept of a prosthesis in which certain commonly used tasks have appropriate trajectories stored in memory, for selection by the user, is attractive. One of the best designs for a complex "feeder arm" provided a complex trajectory and required only a single input, [13]. The designer, Colin McLaurin, many years ago proposed the addition of a second input which would modify the mechanical linkage to meet differing functional trajectory requirements, [14]. This formidable task for mechanical design may not be so difficult in a modern system using computer control.

It should be noted that even the most severe amputation, the forequarter (intrascapulothoracic) amputation, leaves the amputee with the ability to use trunk movement for fine positioning. Thus rough positioning only is required of the powered system.

This comment assumes that functional use of the prosthesis will require full visual monitoring. The possibility of using robot vision to control automatic fine positioning of the terminal device is interesting. However, it is assumed that prevailing size and weight constraints preclude such a development at this time.

Sensing technology is important. Provision of "touch" sensors, either for sensory feedback to the amputee or for closed loop control of function, is overdue. Continuous monitoring of all joint angles will be essential for any form of automatic control.

With respect to automation, even the provision of some degree of automatic performance monitoring and adaptive adjustment promises to be important as these systems become more complex. The concept of adaptive adjustment of gain in a myoelectric control system has been implemented already, [15], and more complete adaptive systems surely will follow.

CONCLUSION

There are severe constraints in developing prosthetic limbs, and the resulting design problems are formidable. Nevertheless, there are many opportunities for application of robotics technology, and the authors are hopeful that synergism will develop between these two exciting fields.

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PHYSIOLOGICALLY APPROPRIATE CONTROL OF A MULTI-DEGREE OF FREEDOM UPPER LIMB PROSTHESIS

-OR WHERE PROSTHETICS MEETS ROBOTICS

DAVID GOW.

Senior Bioengineer in charge of upper limb prosthetics, Bioengineering Centre, Princess Margaret Rose Orthopaedic Hospital, Fairmilehead, Edinburgh EH10 7ED, U.K..

Telephone 031.445.4123

INTRODUCTION

In the field of externally powered upper limb prosthetic devices for the disabled there is a sad lack of practical devices for the bilateral amputee. The lack of suitable control systems for powered devices, the paucity of control inputs available and the lack of knowledge of the human physiological control loop has seriously retarded progress in this area. Historically, however, one of the most complete solutions to date was provided by the pneumatically powered, multi degree of freedom system developed in Edinburgh by Professor David Simpson (Ref. 1).

Professor Simpson recognised that the extant proprioceptive mechanisms still intact in the shoulder articulations of bilateral amputees, could be used to control a small number of degrees of freedom which would provide useful loci of movements for an upper limb device. To accomplish this, each identifiable residual control input was linked to one and only one degree of freedom in the prosthesis; thus shoulder evelation might control the prosthetic arm elevation and so on. Furthermore, he closed the prosthesis/operator loop by mechanically linking the output to the input via a cable. Thus, he produced an 'unbeatable' servomechanism with four spatial degrees of freedom and one prehensive degree of freedom. The control of these limbs was readily learnt by amputees and apparently become subconscious, thus no extra mental load was imposed on the operators.

Professor Simpson believed that the reason that independent parallel control of this number of degrees of freedom was possible was because the proprioception naturally experienced by the amputees in moving their shoulders was being extended via the 'unbeatable' servo system to the prosthesis. Thus he coined the term Extended Physiological Proprioception (EPP).

In the course of more recent research in Edinburgh (Ref. 2), control systems for electrically powered devices have been produced. It is the purpose of this paper to describe this author's intention to apply his recent work on EPP to produce an electrical multi degree of freedom prosthesis for bilateral amputees (with the added possibility that such a development may have applications for other disabled populations in the form of a remote robotic manipulator/'third arm' device).

METHODS

The initial course of action is to take the existing pneumatic prosthesis skeleton and simply replace each degree of freedom's pneumatic actuator with an electrical analogue; each electrical actuator consists of a motor and ballnut device. The power rating of the motor and the size of the ballnut varies depending on joint location. The ballnut is a relatively new British invention developed by RHP Limited and has an anti-runback feature. The control system electronics are then applied to each degree of freedom.

STATUS

At present of the four potentially controllable modules of the arm, namely hand, wrist, elbow and shoulder, a working prototype hand and elbow have been constructed. Both these modules have proved controllable by EPP control methods.

FURTHER RESEARCH

Further refinement of the two modules described is required as well as the construction of the higher powered joint, the shoulder. Redesign of some of the electronic modules may be necessary to cope with larger operating currents and redesign of structural components will also be required to reduce weight. We also intend to look at the possibility of hybrid devices, namely pneumatic electrical ones. For example, a pneumatic shoulder may be more easily achievable than an electrical one. The control method would remain the same, however.

CO-OPERATION

We are interested in co-operating with any centre working on this type of prosthetic research. At present we also have links with The Computer Aided Engineering Centre, at the Department of Mechanical Engineering of Heriot Watt University in Edinburgh.

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DESIGN AND DEVELOPMENT OF AN ELECTRICALLY POWERED PROSTHETIC GRIPPER

M.C. Kemp,
Hugh Steeper Ltd,
Roehampton, London SW15 5EH.

1. INTRODUCTION

Hugh Steeper Ltd, have been providing upper limb prosthetics in the U.K. since 1918.

Our experience in recent years with the increasing numbers of myo-electric hand users has shown that many patients have a need for an alternative or additional terminal device with an improved functional performance.

The myo-electric hand provides acceptable cosmesis with a functional ability which is sufficient for normal use. When combined with supra condylar sockets which make harnesses and operating cords unnecessary the result is a prosthesis which is highly acceptable to patients. The functional limitations of the hand arise because it is a simple gripper, disguised as a hand but without the versatility of the human hand.

2. DESIGN SPECIFICATION

To assess which parameters could be most usefully improved we consulted the patients, occupational therapists, medical officers and prosthetists as well as making our own observations.

The result of this process was a shopping list of improvements which formed the basis of the design specification. These improvements were:-

1. <u>The ability to grasp all kinds and sizes of objects securely.</u>
   It is this function which is most compromised by the anthropomorthic shape of the hand.

2. <u>Closing Time</u>
   The hand can appear slow to the user.

3. <u>Lower Mass</u>
   Although the mass of the electric hand is not a disadvantage to most patients a lighter device is always favourably received, and for patients with short stumps, may make a considerable improvement in comfort.

4. <u>Bulk</u>
   Lack of proprioception makes vision the major source of feedback when manipulating objects and so clear sight lines to the gripping surfaces are essential.

5. <u>Adaptability for special needs.</u>
   Many patients with cord operated prostheses have special appliances for particular needs, interchangeable with their usual terminal device. The ability to replace the standard jaws with specialised ones would allow the myo-electric prosthesis to mirror this versatility.

In addition to these improvements the gripper would be required to be:

1. Compatible with the Steeper Electric Control System, basically this is the battery, amplifier and wiring system which supplies the hand with power and the two logic control signals for open and close.
2. Power consumption must be kept to a minimum. In this application rechargeable batteries are used and the patients are issued with battery chargers which will only recharge 2 batteries at a time so it is important not to exceed this limitation.
3. Self contained drive system and electronic control. Long stump patients will have no room in the socket for components other than the surface mounted battery and its wiring.
4. To suit all prosthetic applications 6V and 12V versions are required.

Using these requirements as a basis for the design specification, each requirement was analysed to establish optimum performance for the gripper and a detailed study made of the two most important considerations, the ability to grasp objects and the closing time.

3. THE ABILITY TO GRASP OBJECTS.

In this instance the term grasp is used to refer to the complete function of holding an object whereas the term grip force refers to the force between the jaw tips. The ability to grasp is an

interactive function of 3 major parameters.
1. The grip force applied by the jaws, to the object.
2. The shape of the jaws.
3. The surface properties of the jaws including their texture, compliance and functional properties.

4. GRIP

It was considered an essential requirement that grip force should not be raised to the value which would cause pain or injury to anyone caught in the jaws.

In practice this means limiting the maximum grip to 60 - 80N. By comparison this force applied between a real thumb and forefinger will cause whitening of the knuckles and rapid tiring of the muscles. Clearly with well designed jaws such a grip force should be sufficient for normal purposes.

5. JAW SHAPE

Consideration of jaw shape also must include the type of movement, and our experience has shown that for amputees, who must use visual feedback only, it is easier to place one fixed jaw alongside an object and allow the other jaw to close onto it, than to hold two jaws equally displaced about the object while they both close on it. If articles cannot be picked up rapidly and with little effort then the single amputee will use his sound limb to place objects in the gripper and double amputees will find the device ineffective.

For this reason we decided that for the initial grasping of objects only one jaw should move and the other should be used for increasing the grip force if necessary.

Geometric studies on the drawing board were carried out to evolve jaw curvatures and lengths which could hold objects of small and large diameter equally well. A long jaw with a large radius of curvature moves first to pick up the object and applies a moderate grip force of 10 to 15 Newtons at the tip and this is often sufficient to give secure grasp. Because of its high tip speed this is referred to as the fast jaw. The shorter or slow jaw remains static until the object is grasped and then may be used to increase the grip force to 60 - 80 N if the patient wishes. Because of its smaller radius of curvature and its pivot position, displaced from that of the fast jaw, movement of the slow jaw pulls large diameter objects into the gripper rather than tending to eject them as can happen with some other jaw designs.

The hooked tips have larger surfaces than those of traditional body powered hooks because the greater grip force generated by the powered gripper enables objects such as pens and knives to be gripped securely between the hook tips, without requiring additional support.

6. JAW SURFACE PROPERTIES

To minimise the grip force required the jaws are lined with compliant rubber surfaces bonded into recesses in the jaw castings. On the inner surface of the hooked tips the liners are closely supported by the castings themselves but to increase their compliance the liners are hollowed out along the inner faces of the jaw curvature.

Along these surfaces the liners are deeply grooved vertically and horizontally to produce a sharp edged tyre thread which wipes wet objects and keys into surface irregularities. On the hooked section the liners have a raised lip around their edge which can key into the shape of objects and also overcomes problems due to any jaw misalignment. The tips of the hooks have metal tips to grip fine objects such as needles.

7. CLOSING SPEED.

Myoelectric amplifiers operate by detecting surface potentials generated by muscular contractions. In this way residual antagonist muscles in the stump may be used to generate the open and close signals to the hand just as they do in the sound limb. Ergonomically this is an ideal means of operation except that the signal to noise ratio of myo-electric signals is high and an integration period of approximately 40 mS is required to establish the validity of the myo-electric input. This delay is discernable by the patient and reduces the sensation of direct control. This delay also occurs when the myo-electric signal is relaxed. Therefore when a patient operates a myo-electric device there will be the following sequence.
1. Initial reaction time of 100 mS: the patient will be unaware of this and so it may be disregarded in the design.
2. Myo-electric signal recognition time of 40 mS. The patient is aware of this delay but it is not a significant factor at this stage of the sequence and is dependant on myo-electric amplifier design.
3. The device closes: in the case of the electric hand, closure from the fully open position takes 1.2 seconds. During this part of the sequence the patient must maintain position relative to the object they wish to pick up, and is very aware of the time taken.

4. The patient reacts and releases the myo-electric signal in a total time of 140 mS as at 1 and 2 above. The patient is again unaware of this time. This sequence suggests that the faster the closing time the better the result for the patient, but this is not so.

When the patient wishes to stop the moving jaw in an intermediate position then he will need to anticipate his own reaction time and the reaction time of the myo-electric amplifier, a combined time of 140mS, now the patient is keenly aware of this delay. Clearly, the minimum distance the jaw can be moved is the distance if will travel in this time. It is important that this distance travelled during the reaction time is not too great both for the sake of operating in confined spaced and so that the patient feels in control of the jaw.

Imagine picking up a china ornament in a gift shop using a device whose jaws dart open by 4 inches when operated.

After experimentation we established a criterion for jaw closing speed, such that a practised user should be able to start and stop the fast jaw at least once during its full travel. This meant that the fast jaw closing time would have to be in the region of 0.5 secs.

8. DRIVE SYSTEM

The requirements of closing time and maximum grip force could not be met by a single velocity ratio with the power available and so a two stage drive system had to be specified.

3 basic systems were considered.

1. A single moving jaw with variable ratio drive.
   This was rejected because of the complexity of execution involved.
2. A 2 ratio drive system operating on one or both jaws sequentially. Again systems based on this concept would have been more complex than the adopted solution.
3. Indepentendly driven jaws operated sequentially under logic control.
   This system was chosen because, although a mass penalty was incurred by the 2 motors, the use of lightweight motors with slightly less power resulted in a saving of 20 gms compared with one larger motor.

The drive systems for the two jaws are similar, consisting of a spur gear reduction driving a non-back driveable worm and nut. The different velocity ratios are achieved by simply having the jaw pivots at different points slong their length. Thus the fast jaw moves through a 100mm arc in 5 seconds to exert a maximum grip force of 15 - 20 Newtons, and the slow jaw moves through an arc of 6mm in 250 mS to produce a grip force of 60 - 80 Newtons. This feature proved to be of great value during the development of the reliable and unambiguous control logic essential for patient confidence.

A continuous open signal from the patient opens first the slow jaw until it stalls the circuit then transfers power to the fast jaw until that stalls.

A continuous close signal from the patient closes the fast jaw until it stalls, then there is a ½ second delay to allow the patient time to relax his close signal and use the lighter grip only. If the close signal persists at the end of this delay then the slow jaw closes until stalled. Should the patient relax his input signal at any point the jaws will stop at that point and opening or closing sequences can be initiated without any ambiguous or inconsistent response.

Although the delay time increases the time taken to achieve maximum grip this proves in practice not to be a problem to the patient as he is able to transfer his attention from the object once the fast jaw grip has been attained. A quicker user may also beat the delay period by relaxing and reapplying the close signal after the fast jaw has stalled. Logic input signals from any source may be used to control the gripper with the same circuit being used for 6 and 12V supplies. Adaptation requires only the removal of an external link.

9. CONCLUSION

A total of 9 prototype grippers have been manufactured and 6 have been fitted to patients including 1 double amputee.

The results have enabled the control logic to be developed and some areas of mechanical design to be refined.

The aim of improved function within a cosmetically acceptable device has been met and bench testing has indicated that the gripper is capable of service life in excess of 750,000 cycles.

10. POWERED GRIPPER SPECIFICATION

Fast jaw grip	15 N	Next jaw opening	90mm
Slow jaw grip	60-80 N	Overall length	146mm
Closing time Fast jaw	0.5 S	Overall width	52mm
Closing time Slow jaw	0.25 S	Overall depth	54mm
		Mass	340gm

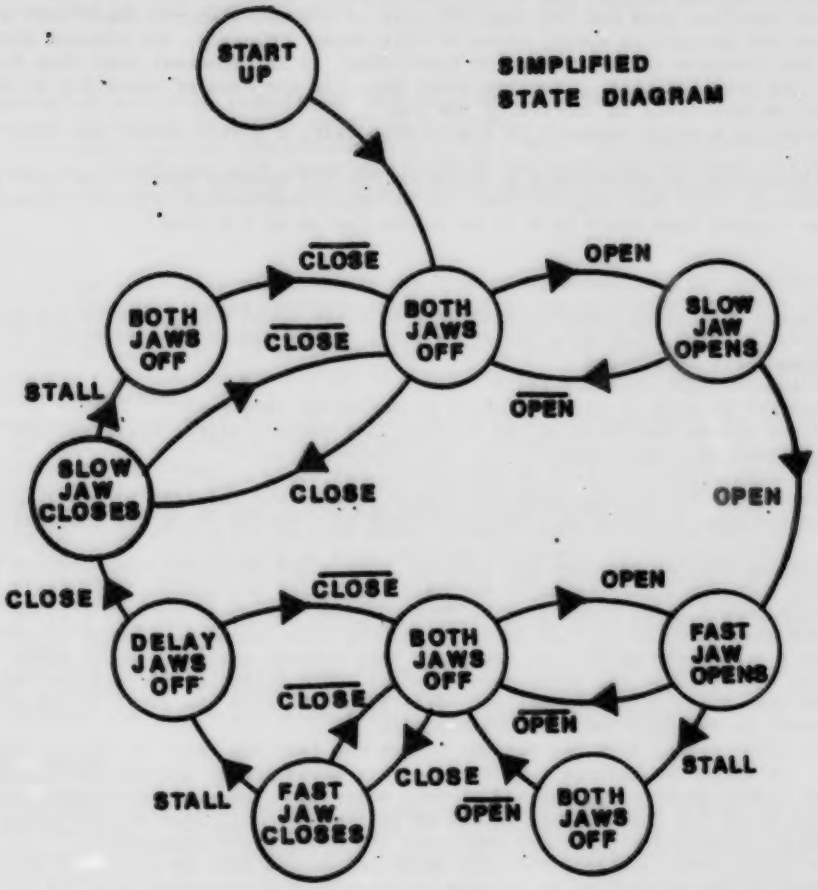

START UP
SIMPLIFIED STATE DIAGRAM
BOTH JAWS OFF
CLOSE
BOTH JAWS OFF
OPEN
SLOW JAW OPENS
CLOSE
OPEN
STALL
SLOW JAW CLOSES
CLOSE
CLOSE
OPEN
CLOSE
DELAY JAWS OFF
CLOSE
BOTH JAWS OFF
OPEN
FAST JAW OPENS
CLOSE
OPEN
STALL
FAST JAW CLOSES
CLOSE
OPEN
BOTH JAWS OFF
STALL

FIG. 1.

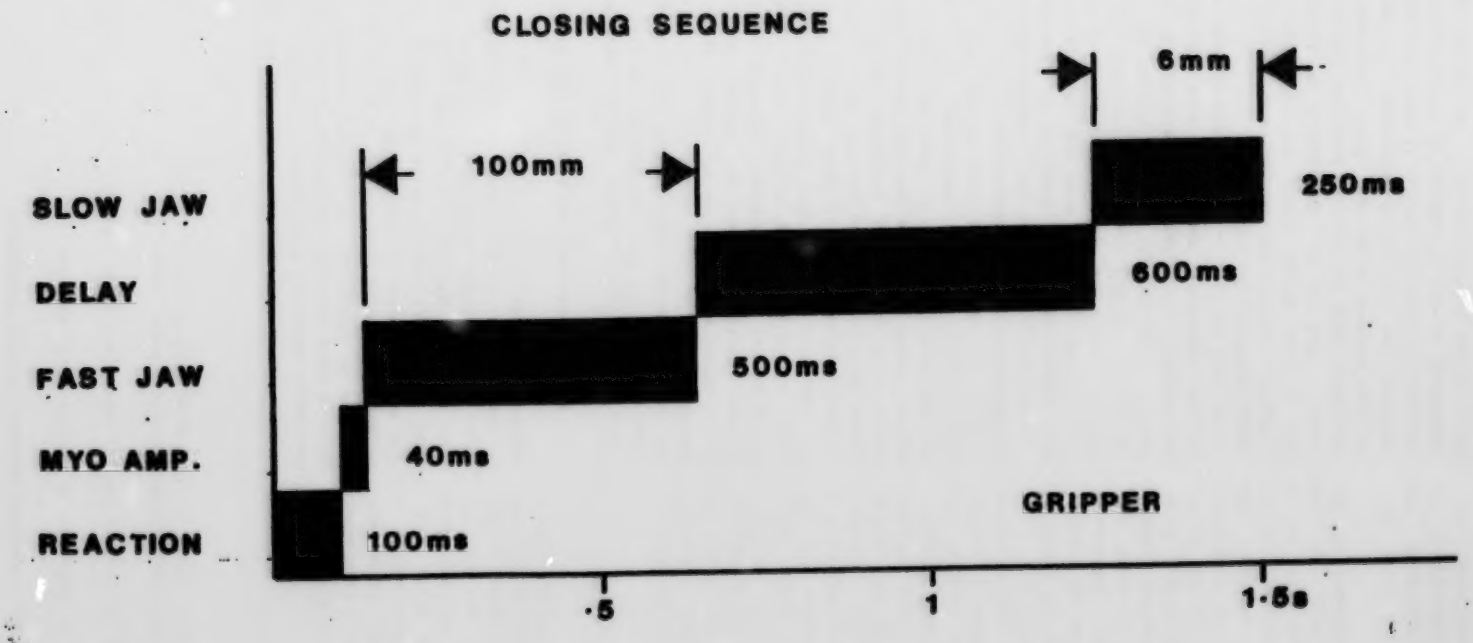

CLOSING SEQUENCE
6mm
100mm
250ms
SLOW JAW
600ms
DELAY
500ms
FAST JAW
40ms
MYO AMP.
GRIPPER
100ms
REACTION
·5
1
1·5s

FIG. 2

Personal Transfer Supporting Equipment For The Handicapped

M. Kume, K. Matsumoto, M. Maekawa and H. Nakajima

Control & Systems Research Center, Sanyo Electric Co., Ltd.

18-13 Hashiridani 1-chome, Hirakata, Osaka, Japan
Telephone: (0720) 41-1161 Telex: 053-472-76

Abstract

This paper reports on analyses, trial manufacture, and experiments in the process of developing a transfer supporting system. This report was supported by the Agency of Industrial Science & Technology of the Ministry of International Trade and Industry. The system will lift and move bedridden people, position them in electric wheelchairs, and move them in such areas as the bath and toilet. This project began in 1983 and we are in the process of completing the second trial model.

1. Introduction

According to a 1987 survey by the Ministry of Health & Welfare, there are about 2,413,000 handicapped people in Japan and the number is increasing yearly. The census in 1985 placed the number of elderly people, aged 65 years and over, at 10.3% (more than 12,000,000) of Japan's total population of 121,050,000. This means that the number of people requiring assistance because of a physical handicap is also increasing. Furthermore, because the job of lifting and moving bedridden handicapped people or other patients from their beds is done mainly by hand, it puts a considerable stress on the lower back of the person doing the moving. Therefore a growing number of cases of recurring back pain are being reported by nurses and other helpers.

In order to mechanize this task, the Agency of Industrial Science & Technology under the Ministry of International Trade & Industry initiated a 6-year plan, starting in 1983, in which four companies were commissioned to develop transfer supporting systems for the handicapped. These systems would allow bedridden patients to be lifted and moved to a bathroom or to other areas either with a helper or by self-operation. The project calls for simultaneous development of two system types, a high-performance type and a personal type. Sanyo Electric Co., Ltd., is solely responsible for the development of the personal type.

As for development progress, the first trial model was completed in 1985 and evaluated. The evaluations indicated that the mobility of the transfer supporting system was insufficient, the overall weight (220 kg) was excessive, and the supporting operations were somewhat difficult. In spite of these problems, the system functions were found to be effective. We are now involved in designing the second trial model, which is scheduled for completion in March 1989. We will be doing experiments and analyses to resolve the above mentioned problems. During the final six months of the project, a practical evaluation will be carried out at rehabilitation centers and other medical facilities.

2. Present Technology and Developmental Goals

More medical care machinery and equipment are being developed and sold now than in the past to help move, transfer, and position patients and handicapped people.
The electric wheelchair is an example of such devices. Currently, there are various electric chairs to aid the handicapped according to the extent of their handicap or their needs. There are some that feature the highest level man-machine interface devices which enable handicapped with minimum functions to operate them. Others with a steering mechanism devised to improve manual operations and with greater transfer functions (1), (2), (3). There are also those with enhanced movement functions, i.e., the raising and lowering functions of the seat, the reclining function, and accessories.

There are a number of bed transfer devices. Belt conveyance devices installed on stretchers allow people to slide from bed to stretcher. Moreover, there are devices which are hung from the ceiling to lift the body or devices with a special robot arm that lift the patient and the bed together (4). But, when machines do bed transfer operations, the present belt conveyance is the most appropriate to limit the physical and mental burden on the patient.

However, patients who are bedridden want to be able to move around freely and not depend on others. This is the idea behind an electric wheelchair which has transfer functions that allow for easy movement to the bed. Still, this type of equipment has yet to be developed. It would require a fundamental redesign of their respective mechanical aspects to combine an electric wheelchair and bed transfer device. Also, because we

have both mechanical control technology which effectively connects each function and multifunctional microcomputer technology, we now need high technology that will combine such essential technologies, i.e., man-machine interface technology to carry out various operations. Every year the number of handicapped people increases, and with the trend toward an aged society it is important to develop safe support robots to assist people who have lost certain abilities. With this in mind, we have started this project and our goal is to develop a transfer supporting system with the following functions:

1. Transfer patients from system to bed in a lying position.
2. Transfer and support patients in the sitting position between the system and the toilet.
3. Posture shifting of patients transferred by the system (lying position to the sitting position).
4. Height adjustment for the transfer device mentioned above.
5. Flexible movement functions.
6. A remote control operations panel to input operations and give a conditions display.

3. Mechanical Design of the System

The personal transfer supporting system resembles an electric wheelchair, having a locomotive base with four wheels supporting a reclinable chair structure and is driven by a DC power supply of batteries.

Next, we will discuss the mechanical functions of the personal movement device, the height adjustment device, the posture shifting device, and the physical transfer device.

An assembly diagram for the movement device is shown in Fig. 1. The movement device has two drive wheels on the right and two slave wheels on the left for backward and forward motion. Thus, the mechanism to drive the wheels and the steering drive mechanism have become one. The drive wheel revolves around the perpendicular axle at a constant distance (85 mm). These drive systems are compactly designed and do not exceed the wheel height (220 mm). The controller is installed in the space between the wheels. Each motor senses position and speed through an encoder. The steering angle is sensed by a potentiometer (described later). Various motion modes are possible with this mechanism since the home position for steering can be set at any position. When the transporter approaches a bed, it moves sideways. Casters with a small radius are used to allow the slave wheels to move under the bed. By this, the physical transfer device can move even closer to the patient.

The height adjustment section is constructed of two distorted X-links, each consisting of two bent beams, positioned in parallel. This construction provides light weight and structural strength while allowing for a vertical stroke length of 200 mm which enables the compact storage of its own drive system and other devices between the X-links. The angle between the X-link can be changed by moving the trapezoidal screw forward or backward. The motor senses position and speed by an encoder.

The posture shifting section is a 4-jointed link construction in which the backrest and legrest of the reclinable seat frame are joined by a single pipe. The backrest, seat, and legrest can move simultaneously from a stretch position to a suitably angled seating position. Also, the backrest and legrest are able to slide individually on the supporting frame, forward and backward along the 4-jointed link plane, to prevent the person's body from slipping from the contact surface during posture shifting.

The seat section can slide in a sideways direction. This allows the seat to be removed from above the toilet when a person goes to the toilet. It then returns in the opposite direction to which it was fed. For posture shifting, a 4-jointed link changes position by pushing the backrest and the trapezoidal screw toward the seat. Each motor senses position and speed through an encoder.

The assembly of the physical transfer device is shown in Fig. 2. This is the transfer mechanism used in the backrest but the same kind of mechanism is featured in the seat and legrest. A plate is pushed from the transfer supporting system in a sideways direction and inserted between the person's body and the support surfaces. After the person's body is placed on the plate, it is transported on the equipment side. Fig. 3 shows the mechanism of this transfer device. To ease insertion, the plate section is equipped with two endless belts, one for the person's contact surface which is guided by the plate and the other for the support surface which is guided by the guide bars. The upper belt is kept on top of the belt holder which can slide toward the device itself. Thus, the belt holder and the mechanism for locking the belt of the transfer device have become one. When the upper belt is locked in the transfer device, the belt is in relative motion with respect to the plates because of the transfer plate feed. When the lock is detached, it moves with the plate. Since the lower belt is fixed in the main part of the transfer device, it is usually in relative motion with respect to the plates. The belts are fed so as to prevent slipping between the belt and the contact surface during insertion. The belts are fed by the control of one plate drive motor and one electromagnetic brake which locks the upper belt. The transmission of motive force for the plate feed mechanism and the belt lock mechanism via a timing

belt is very successful because the device is thin.

The plates are made of 5 mm carbon reinforced plastic and the overall thickness, including the belt feeding mechanism, is low at 30 mm.

Each motor senses position and speed through an encoder.

The feed mechanism for the height adjustment device, the posture shifting device, and the transfer device, detects possible motion ranges with two limiter switches each. One more limiter switch is set within the possible movement range and that point becomes the point of origin for the equipment.

The mechanical design of each piece of equipment is shown in Table 1.

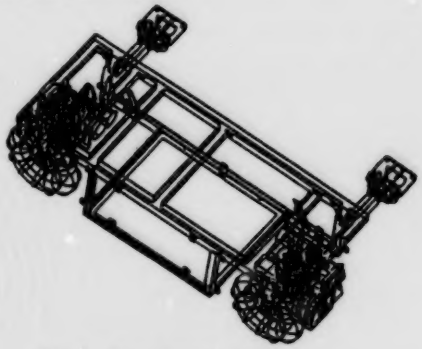


Fig. 1 The movement device

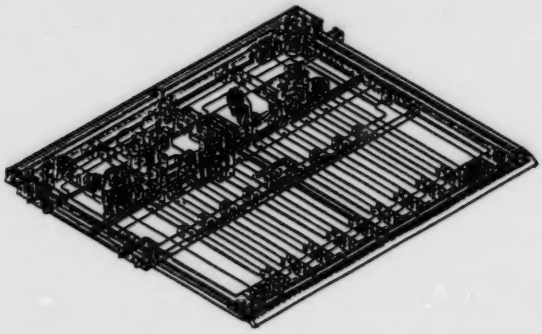


Fig. 2 The physical transfer device

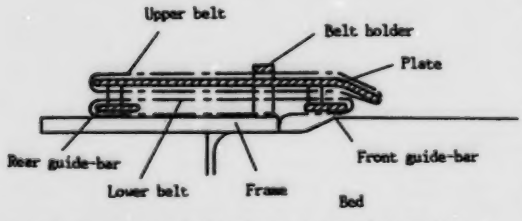


Fig. 3 Mechanism of the physical transfer device

Table. 1 Specifications of mechanical design

Movement device	
Dimension	880W×900L×265H
Drive wheel	650×φ220, rubber tire with tube
Slave wheel	320×φ100, castor
Steering motor	DC 60W (24V)×2
drive motor	DC 200W (24V)×2
Max speed	4.4 km/h
Weight	50 kg
Height adjustment section	
Dimension	340W×660L
Form	X links, fed by ball screw
Stroke	290 (minimum height 125)
Driving motor	DC 100W (24V)
Weight	22.5 kg
Posture shifting section	
Dimension	340W×1000L at stretch
Form	4-jointed Link with sliding function
Frame angle	Backrest 0°(horizontal)~75°
	Seat 0°(horizontal)~7°
	Legrest 0°(horizontal)~45°
Driving motor	DC 40W (24V) for reclining
	DC 60W (24V) for sliding on backrest
	DC 40W (24V) for sliding on legrest
Weight	21 kg
Physical transfer section	
Dimension	630W×720L for backrest plate
	630W×520L for seat plate
	630W×420L for legrest plate
Form	Belt feeding by belt-lock mechanism
Plate material	Carbon Fiber Reinforced Plastic
Plate stroke	420
Driving motor	DC 40W (24V)×3

4. Hardware of the Control Section

The composition of the control section hardware is shown in Fig. 4.

The control section is a STD-BUS type and consists of four motor drive boards, one CPU board, and one composite board. The motor drive boards control the three motors simultaneously by PWM voltage control using the encoder's pulse feedback. The CPU board and the composite board are connected by a serial communication link (RS-232C). The composite board sends various sensor information to the CPU board and the CPU sends ON/OFF switch control information back to the composite board.

The control panel is also connected to the computer through a serial communication link (RS-232C). The control panel has 10 selection keys, 2 execute keys, and a joystick for controlling various equipment. Besides sending commands to the CPU board, it receives operational commands from the CPU board and data about the overall equipment condition. It also indicates this information by LED display. The control panel is controlled by an 8-bit microprocessor.

In order to develop a low power-consuming, lightweight and compact control section, we used CMOS and high-density packaging for components.

The specifications for the control section are shown in Table 2.

Fig. 5 is a schematic diagram of the control panel. The handy, compact control cassette only has the keys necessary for transfer operations and can easily be removed from the main panel. We took transfer assistance operations into consideration in order to have safer, single-handed transfers.

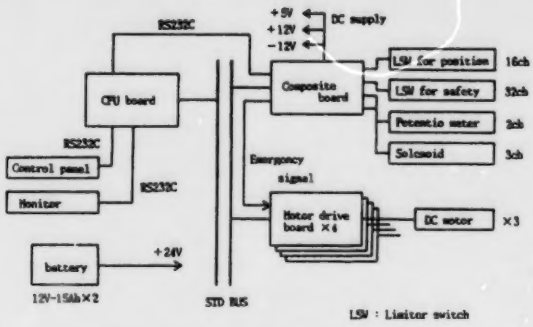


Fig. 4 The composition of the control section

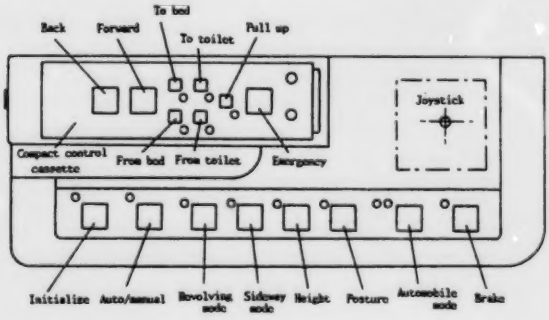
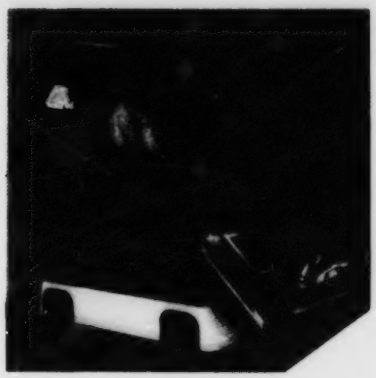


Fig. 5 Control panel

Table. 2 Specifications of controller hardware

CPU board	
Microprocessor	16bit, μPD70116D-8 (NEC co.)
Clock	8.144 MHz
ROM	128 byte
RAM	128 byte
Serial interface	RS232C 3ch
Interrupt	NMI 1 level, INT 22 level
Power consuming	1.8 W
Motor drive board	
Control method	Closed-loop control by FG servo
Objective motor	24V×(rotor current) 7A (max 20A)
Power consuming	2.2 W
Composit board	
Microprocessor	8bit, HD63701Y0 (Hitachi co.)
DI data processing	32ch for safety switch
	16ch for positioning switch
Solenoid driver	3ch, 24V-12W
A/D conversion	2ch, 8bit for potentio meter
DC/DC conversion	output 5V(4.0A), +12V(0.6A), −12V(0.1A)
Serial interface	RS232C 1ch
Control panel	
Microprocessor	8bit, HD63701Y0
DI/O data processing	Key switch×16, LED×14, buzzer×1
A/D conversion	2ch, 8bit for joystick
Serial interface	RS232C 1ch



At the chair position

At the stretched position

Photo 1 The second trial model

Thus, the design of the second trial model stressed light weight, lower power consumption, and improvement of both mobility and operability. This particular design allowed for development of equipment with an overall weight of less than 150 kg and 4 hours of continuous operation by a DC power supply requiring only two batteries (12 V, 15 AHx2).

An external view of the second trial model is shown in Photo 1.

5. The Motion Control of Each Device

The movement device is controlled by rotating the joystick in one of three possible travel modes, the home position of which is set as shown in Fig. 6. Position a) is the automobile mode and the center line of rotation is on the X axis. It controls the steering angle by stepping from infinity to X min in 32 steps depending on the

left or right movement of the joystick. Straight line or curved travel are possible. Forward and reverse are also controlled by forward or reverse direction of the joy stick. Position b) is the sideways mode and it steers by shifting the front and rear wheels 90 degrees each in the opposite direction from the steering home position of the automobile mode. This mode is used to approach the bed. Left and right movement is achieved by operating the joy stick in the left or right direction. The front and rear wheel rate of speed can be changed by operating the joy stick in a forward or reverse direction. Position c) is the revolving mode and left or right revolutions are carried out by left or right operations of the joy stick. The center line of revolution is moved forward or backward on the Y axis by operating the joy stick in the forward or reverse direction. We presume that the movement device will function much the same as an electric wheelchair. Consequently, we have carried out a number of performance tests for the electric wheelchair in the automobile mode as determined by JIS (Japanese Industrial Standards). We obtained satisfactory performance results for maneuverability. Each travel mode corresponds to one switch on the control panel. However, since the steering axis and the wheels have a fixed offset when the mode is changed, they are synchronized with the steering motion and the wheels are driven, and deviations in the vehicle are controlled as much as possible.

The height adjustment mode is entered by a key switch on the control panel. The direction of movement and the speed are controlled by forward or reverse movements with the joy stick.

The posture shifting device operates similarly but in order to prevent the body from slipping from the backrest and legrest, the slide mechanism has to be synchronized with changes in the angle of the positioned body. Fig. 7 shows an example of corresponding movements of the human body with the backrest and legrest. The backrest and legrest revolve around the center points O_1 and O_2. If we divide the human body into sections, i.e., the hip joint and the knee joint, then we presume the links BA, AP, and PL. Here, link AP is fixed to the seat. The slippage between the end of link B and the backrest and the end of L and the legrest can be calculated using the change in positional angle O_1 and O_2. In respect to O_1 and O_2, the hip joint point A and the knee joint point P positions are determined by referring to body dimension data (5). By taking the link lengths r_b, r_l as the parameters, since $\theta_b=0$, $\theta_l=0$ we get an integral value for the slippage of $S_b(\theta_b)$, $S_l(\theta_l)$. Conversely, the slide device for the backrest and legrest are based on the curves S_b, S_l. If we take the positional angle of the body θ_b, θ_l as the positional followup control, then we can prevent slippage with the body. The actual slide control is $r_b=400$, $r_l=200$. As a result, there is a comfortable posture shift with hardly any slippage.

The personal transport operation is controlled by the transport plate and belt lock mechanism. For bed transfers, i.e., when the body is prone, the backrest seat and the legrest devices are synchronized and are pushed out at the same time. When transferring a patient from a bed to the device, it is necessary to follow the procedure below:

1. Bring the device near the bed and roughly adjust the height to the bed.
2. Finely adjust the height to the bed.
3. Move closer to the patient (at this time the caster will slide under the bed).
4. Place the transfer device on the bed (lower the device).
5. Transfer the patient from the bed.
6. Raise the patient from the bed.
7. Bring the device away from the bed.

The procedure above is hand-operated and somewhat complicated so it is easy to make mistakes. Therefore, on the actual transfer supporting system, steps 2 through 7 are done automatically. Step 1 is done after a posture shift and before approaching the bed. We think it would require a large-scale induction device to do this automatically and that is not practical on the personal type of transfer supporting system; thus, it is hand operated. Steps 2, 4, and 6 use contact sensors attached to the physical transfer device and make height adjustments while maintaining an appropriate distance from the bed. In step 3, a distance sensor and a contact sensor are used to adjust the position of the system in relation to the bed until the system contacts the bed. During the patient transfer stage in step 5, the upper belt is locked when the transfer plate is pushed out and is released when the patient is placed on the plate. You must always be aware of the safety of the patient when performing a personal transfer operation. Set the key switch to the ON position to execute the control sequence from step 2 to step 7 or when reversing the sequence. In the OFF position, the entire sequence comes to a stop. Releasing the key stops the sequence. You can reverse the sequence by selecting another key, in the event of emergency. The process of transporting back to the bed is similar but the reverse of the procedure mentioned above.

Transfer from the bed to the toilet is done by seat positioning. The procedure is similar to that of bed transfers. Due to the structure of the transfer device, there is a limitation on how far the seat position can be extended. Therefore, three transfer devices are extended and after the patient is moved above the toilet, the transfer device for the seat section and the sideways slide

device work jointly and the seat is removed from beneath the patient. During these operations, the patient is supported by support attachments.

All the equipment mentioned above can be selected using the 10 select keys on the control panel. The 8-bit microprocessor of the control panel sends data input from the keys and converted A/D (analog to digital) data from the joy stick to the controller CPU board. It receives data for the LED display in order to show the overall condition of the equipment.

The 8-bit microprocessor of the composite board sends sensory data and converted A/D data from the potentiometer to the controller CPU board. The microprocessor also receives a clock signal from the CPU board and monitors abnormalities in the main computer. It senses the limiter switch used for safety and will immediately cease operations of any equipment.

The 8-bit microprocessor is an internal ROM chip and the control software is written in assembly language. Since the host computer is involved in many areas, such as control of the various devices mentioned above and data communication with the control panel and composite board, a real-time OS MTOS 86 (mfd. by IPI) was used to effectively develop its software.

C language (from White-Smith Co.) was used to develop applications, and the interface for the MTOS is written with ASM 86.

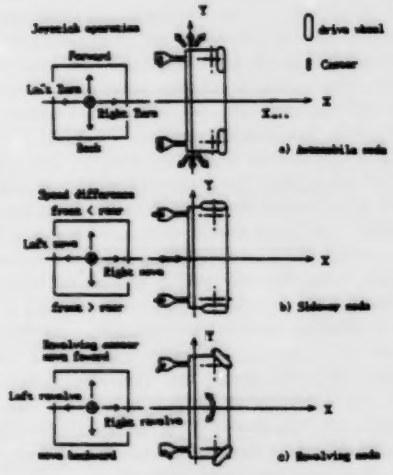


Fig.6 Control of the movement device

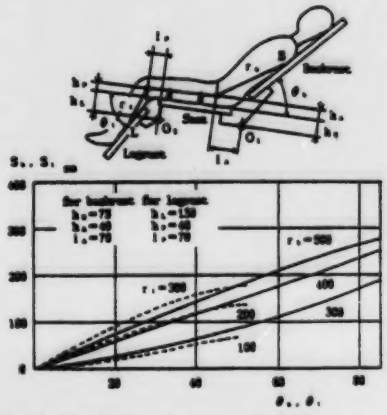


Fig.7 Simulation of posture shifting

6. Physical Transfer Test

We are actually conducting transfer experiments for the transfer device and making improvements. The initial transfer device was a mechanism which extended a plate for horizontal transfer from the body of the transfer support machine. At that time, there was a large amount of resistance when the plate was extended. With ordinary spring mattress beds, the patient sank deep into the bed and the plate was too high for insertion. The body was transported onto the plate after overcoming the height difference. In the transfer device, itself, the plate drive device and part of the belt lock mechanism are built into the frame which guides the transfer plate. As a result, the height of the plate could not be lowered close to the bed. As shown in Fig. 8, the forward edge of the plate is curved 30mm (max. 30°) to make it easier to insert. If the forward edge is too low and comes in contact with the surface of the bed, it is possible for the sheet of the bed to become entangled when the upper belt is in motion. To alleviate this problem, we raised the height of the forward edge (h) to 15 mm in relation to the front guide bar of the lower belt. Now let us consider the geometric relationship. Transferring relies on the shape of the object but in the case of human beings, the front edge of the plate touches the body initially. Now let the curve of the front edge of the plate be r, the radius of the circle Rm and one side are Rm as a cross sectional model of the human torso. Let us assume the other side is connected to the rectangle 2L. If we assume that the bed sinks uniformly S mm with gravity M, and if we ignore deformations of

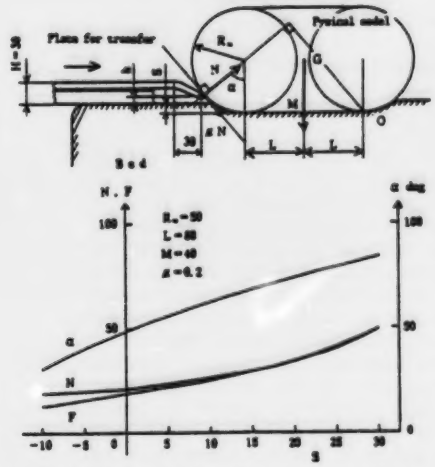


Fig. 8 Simulation of physical transfer on a bed

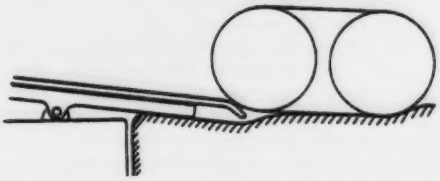


Fig. 9 Future design of the physical transfer device

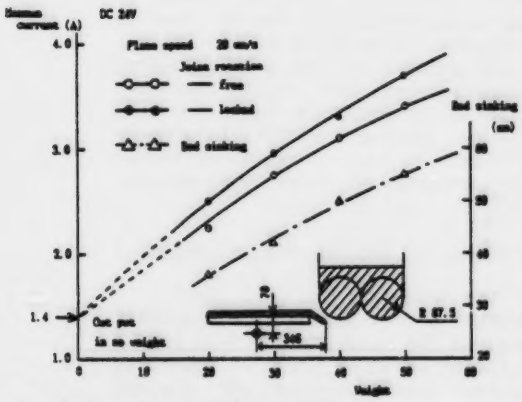


Fig. 10 Experiment of physical transfer

the cross-sectional model, the directional angle α of the body at the time of plate insertion and the slide of the plate is:

$$\alpha = \cos^{-1}\{(R_0-(s+h))/(R_0+r)\}$$

If we let N be the resistance at the point of contact and μ be the coefficient of kinematic friction on the transfer plate, then at the time of insertion, when we let the human body rotate around the center point O then the mechanical relationship

$$N(R_0\tan\alpha + 2L)\cos\alpha = ML$$

holds true. Here the necessary drive force F is derived as follows:

$$F = N(\sin\alpha + \mu\cos\alpha)$$

Fig. 8 shows α, N, F with respect to the depth S when r=2.5 mm, R_0=50 mm, L=80 mm, M=40, and μ=0.2. We know that the larger S the larger the plate drive force is required. When α is 30° or less, the contact point corresponds to the area from the front edge of the plate to the flat area. We know from the above that when you reduce resistance at the time of insertion, the position of the plate must be lower. We assume that when S becomes negative, the transfer supporting system presses on the surface of the bed and the height of the plate is relatively low. This method allows for smooth insertion but it is difficult to do because of the strength and weight of the frame of the system.

We are investigating the mechanism in Fig. 9 as a possible solution. The transfer equipment itself freely rotates and when the plates are inserted, the front edge of the plate sinks into the bed due to insertion pressure. Fig. 10 shows the results of transfer experiments in which a revolving joint is installed 345 mm from the front edge of the plate and 70 mm below the surface of the plate. The transfer object as shown in the figure was a vinyl chloride container that was 450 mm long and had a uniform profile. A rubber sheet was wrapped around the R section and the surface was covered with cotton. The weight of the container was adjusted with gravel. The depth to which the container sank into the bed was measured. In the experiment, the lower surface of the frame of the transfer equipment was aligned with the surface of the bed. The speed of the plate movement was constant from the beginning of insertion and the output current to the drive motors was recorded until the plate moved 150 mm. In the figure, the maximum values from the start of insertion to 150 mm are plotted and a comparison is made between the machine freely revolving and in a fixed position. You may consider that the value of the output current is equivalent to the insertion resistance. As a result, the insertion is smoother than was the case in former

equipment. This confirmed the effectiveness of the mechanism which we mentioned earlier. We also know that adding a slight angle (0-5°) makes plate insertion smoother.

7. Conclusion

We are aiming to develop a transfer supporting system for the handicapped and are carrying out analyses, trial manufacture and experiments to design such a system.

We have used an electric wheelchair or one with transfer functions in order to design such a system. Furthermore, we have gotten good results with transfer functions to a bed or toilet. These are achieved with a system that is compact and lightweight as well as safe.

For control, we developed a highly dependable multi-CPU and serial communication structure and employed CMOS components and high density mounting to achieve compactness and low power consumption. The control software allows people not used to the equipment to easily operate the system. They can safely select the control for each device through 10 menu keys on the control panel. Bothersome hand operations can be done automatically.

For the posture shift and transfer operations, we have reduced the physical and mental strain of the patient as much as possible. This is well reflected in the controls. There is still room for improvement in the mechanical aspect of the transfer device, but the system indicates the direction of research for the future.

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Second Prototype Patient Lifting Arm of the Transfer Supporting System for the Handicapped

Koji Yamada, Akihiro Ooka, Kenji Okamoto,
Kimizo Ono, Yasutugu Doi and Yuji Kohsaka

Sumitomo Electric Industries, Ltd.

1. Introduction

At the present time, in order to lift a physically incapacitated person or a patient out of a bed and move that person to the toilet or bath, the help of another person is usually required. Because this task is one which requires physical strength in an awkward, bent-over posture, a load is exerted on the lower back, and many nurses and family members taking care of such persons suffer from lower back pain.

Under these conditions,because a transport apparatus (a so-called patient care robot) capable of lifting a patient out of a bed and carrying him or her to the toilet or bath would not only lighten the physical strain on nurses and family members, but would also respond to the demands of the patients themselves for greater independence and self-reliance, there is considerable social need for such an apparatus. Not only would such a patient care robot make a valuable contribution to the 780,000 (1980 survey conducted by the Ministry of Health and Welfare) physically incapacitated person in Japan who require daily assistance in their lives, but it is also of vital importance to Japan's rapidly aging society.

One important technological aspect of a patient care robot is the patient lifting arm which lifts the patient out of the bed and transfers him or her to the robot. It is necessary to develop both a method for lifting the patient securely without subjecting him or her to any pain and the actual mechanism which will carry out that method. In addition, in order to provide the apparatus with a certain degree of autonomy and to ensure safety, it is also necessary to construct a feed-back control system which uses enviroment sensor signals to detect the locations of the patient and the bed.

Based on the background described above, since 1983 our company has participated in the "Transfer Supporting System for the Handicapped" of the "National Research and Development Program for Medical and Welfare Apparatus" sponsored by the Agency of Industrial Science and Technology of Japan's Ministry of International Trade and Industry. As part of the project, we have been working on the development of a patient lifting arm. In the three years up through 1985, we built a first-stage prototype of a patient lifting arm and checked its patient lifting functions. Since 1986, we have been working on the development of a second-stage prototype which is lightweight, battery-powered, and capable of lifting a patient out of a low bed. That second-stage prototype is expected to be completed in 1987 fiscal year, so we are writing this report to announce its development.

2. Outline of the patient lifting arm

Figs. 1(a) and 1(b) show the the second-stage prototype patient lifting arm. Although in the figures the prototype is placed on top of a hand pushcart which is not equipped with a drive mechanism, this prototype is designed to be installed for use on an omnidirectional vehicle. The omnidirectional vehicle will make it possible to move the patient lifting arm anywhere in the hospital, to be placed at patient bedside in order to lift them out of the bed, and to carry them to the toilet, bath, etc. This device is capable of changing configuration from a stretcher type configuration [Fig. 1(a)] to a wheelchair type configuration [Fig. 1(b)]; the stretcher type configuration is used when lifting the patient out of the bed, and the wheelchair type configuration is used when transporting the patient.

This patient lifting arm accomplishes the necessary patient lifting functions through the design described below.

(1) Horizontal slide plates with belts attached to them are inserted between the patient and the bed, and these are used to lift the patient out of the bed without subjecting him or her to any pain. Furthermore, the drive of the belts and the drive of the slide plates are performed separately, and the structure is enclosed in a compact unit. This has made it possible to add functions which were not found in previous transport devices, such as being able to drive the belts separately in order to adjust the position of the patient on the device, and a two-stage extension operation wherein the device is first placed on the bed before lifting the patient, thus making the patient lifting arm easier to use.

(2) The control system for approaching and lifting the patient while using sensors to detect the patient and the bed is accomplished by a hierarchical control system which uses microcomputers and two types of sensors, opto-electric proximity sensors and two dimensional tactile sensors. Especially for the sensors which detect the patient while he or she is on the device, we developed large sensors which use a new type of signal detection method. [See reference(1).]
In the following sections we will explain the details of the mechanism and control system of the patient lifting arm.

3.Mechanism

The arrangement of the mechanism of the patient lifting arm for the first-stage and second-stage prototype consists of three lifting units with flat plates which slide horizontally mounted onto an arm unit for changing the configuration. In addition, the patient lifting arm has functions for whole system elevation and sliding.
All of the mechanism are driven by DC servo motors. The turning angle and speed are detected by using a rotary encorder or a potentiometer. Fig.2 shows the overall composition of the mechanisms, and Table 1 shows the specifications.

3-1.Lifting units

The lifting of the patient is accomplished by inserting the horizontal slide plates (insertion plates) of the lifting units in a stretcher type configuration between the patient and the bed, and then the patient is taken onto the device. Thus, it is important for these plates to be constructed in such a manner that they can be inserted smoothly without subjecting the patient to any pain or discomfort. With this patient lifting arm, this is accomplished through the use of insertion plates with belts attached to them.

As shown in Fig.2, each of the insertion plates actually consists of the two plates, one on top of the other, and the belts are attached to each of these two plates. The two ends of the belt attached to the upper plate are wound around belt rollers,and this belt can be driven independently of the insertion plate. In addition, the two ends of the belt attached to the lower plate are secured to the base at the front of the unit. These belts function to reduce the frictional resistance which occurs when the insertion plates are inserted between the patient and the bed. Furthermore, in order to reduce that frictional resistance even further, in addition to keeping the total thickness of the insertion plates as thin as possible (12mm), the front edge of the plates which first come to contact with the patient are bent to a taper shape with the object of softening the impact force applied to the patient.

Fig.3 shows a schematic of the patient lifting principle. When inserting the insertion plates, the rolling velocities of the belt rollers are controlled so that, with respect to the velocity V1 of the insertion plates, the velocity V3 of the upper insertion plate belt is V3=0 and the velocity V2 of the lower insertion plate belt is V2=2× V1. In this way, the movement of the belts at the front ends of the

insertion plates is as indicated by the arrows in Fig.3, thus preventing the patient's clothing or bedsheets from becoming caught. Furthermore, because the relative velocity between the patient and the belts is zero, there is no friction generated between the patient and the belts. Because any friction acting upon the insertion plates is determined only by the dynamic friction between the insertion plates and the backs of the belts, this friction coefficient has been kept as low as possible. After the patient is positioned on top of the insertion plates, the operation direction of the insertion plates is reversed (the velocity is -V1), and the belt rollers are controlled so that V2=V3=-V1, thus moving the patient onto the device. The lifting units which operates under the lifting principle explained using Fig.3 are an extremely compact design, with all of the drive mechanisms located to the rear of the insertion plates. This compact design makes it possible to use a two-stage extension operation wherein the device is first placed on the bed in close proximity to the patient and then the insertion plates are slid between the patient and the bed. This in turn allows the size of the insertion plates to be just slightly larger than the shoulder width of the human body. Conventional stretchers not capable of this type of two-stage operation had to use a technique whereby the insertion plates were slid between the patient and the bed from the end of the bed. Thus it was necessary that they use insertion plates which were approximately as wide as the bed, which increased the width of the device itself and made it difficult to handle.

In addition, with this second-stage prototype, because a full-flat type lifting unit, in which the entire belt winding mechanism is located below the insertion plates, is used at the shoulders of the patient, there is no interference between the patient's shoulders and the belt winding mechanism, thus ensuring greater comfort for the patient. (Refer to Fig.1.)

Fig.4(a) through 4(d) show consecutive photographs of the patient lifting process. Figs. 4(a) and 4(b) show the insertion operation, and Fig.4(c) shows the retracting operation. With these lifting units, because the belt rollers can be driven independently of the insertion plates, even if, as shown in Fig.4(c), lifting is insufficient with the insertion operation alone and at the end of the series of operations the patient's shoulders are still resting on the bed, the belt winding operation can be performed in order to, as shown in Fig 4(d), move the patient to the center of the lifting arm. This function is another feature of this device. Note that the operation for lowering a patient who is on the device onto the bed is performed by executing the sequence of operations shown in Figs.4(a) through 4(d) in the reverse order.

3-2. Configuration changing arm unit

The role of the configuration changing arm unit is to change the relative positions of the three lift units from a stretcher type configuration [Fig.1(a)] where the lifting plane is horizontal to a wheelchair type configuration. Although a system with three degrees of freedom, wherein the three lifting units for the back, hips, and legs could each be adjusted independently, was used in the first-stage prototype, the hip and leg sections are driven by a single actuator, and the overall device has two degrees of freedom consisting of the back section and the hip-leg section. Furthermore, with the second-stage prototype, in order to make the device a power-saving type, pneumatic type springs are used to balance the load.

3-3. Height adjusting mechanism

The height adjusting mechanism consists of a slide mechanism, which makes possible the two-stage extension operation described earlier, and a link mechanism for vertical movement (See Fig.1). Fig.5 shows a schematic of the height adjusting mechanism. As shown in Fig.5, a scissors joint link mechanism is used as the height adjusting method.

In the first-stage prototype, a single-X link mechanism with one scissors joint link assembly was used and the stroke provided by that mechanism is shown in Table 1. In the second-stage prototype, a double-X link mechanism with two parallel scissors joint link assemblies is used, thus reducing the amount of power required for driving the mechanism (Fig.6). Furthermore, in the second-stage prototype, pneumatic springs are used at the positions indicated in Fig.6, and these pneumatic springs further reduce the amount of power required. Thus effect of these pneumatic springs on reducing the amount of power required is shown by the second term of the following equation.

$$F = W \cdot \cot(\alpha) - \frac{P \cdot d \cdot \sin(2\alpha - \theta)}{\sin \alpha \cdot (L^2 + d^2 + 2 \cdot L \cdot d \cdot \cos(2\alpha - \theta))^{1/2}}$$

The stroke of the height adjustment mechanism of the second-stage prototype is shown in Table.1.

4.Control system

The patient lifting arm has the capability of the patient out of the bed by executing a sequence of operations while using several different types of sensors to detect the positions of the bed and the patient. Although this approaches the completely automated systems which can be expected to be realized in the not-too-distant future, even if its application were limited to operation by a nurse or other person assisting a patient, a certain amount of automatic operation can make the device much more convenient to use. In this section, we would like to discuss the control system, sensing functions, and operation sequence used to achieve this automatic operation.

4-1.Hardware used in the control system

In the second-stage prototype of the patient lifting arm, we built a control system based on the new concept of a decentralized installation method. With this concept, the patient lifting arm is divided into several mechanism blocks, and a local control system which controls only the corresponding mechanism block is installed inside that mechanism. This is illustrated in Fig.7. This method provides the following features.

1. There is no need for a large space in which to install the control system, and the individual local control system are easily built into the corresponding mechanism.
2. Each of the local control systems simply has to be provided with the program for controlling the corresponding mechanism module, so programming can be accomplished easily.
3. By using a data transmission line, the amount of wiring required inside the mechanism can be greatly reduced from that required by a centralized control system. We have designed controllers for each of the local control modules using a 16-bit microprocessor for the lifting unit mechanisms and an 8-bit microprocessor for the configuration changing arm unit mechanism. The software servo system is capable of simultaneously controlling multiple DC motors, and also of analyzing the signals from environment sensors. In addition, another 16-bit microprocessor is used for the general control module, thus giving the control system of the patient lifting arm a total of seven microprocessors.

The data transmission line uses a serial communications circuit with a loop configuration in which the individual control modules are nodes. The outlines of this system is shown in Fig.8. We were able to design the system so that only one cable was required between the control modules, so the amount of wiring required was greatly reduced. As shown in Fig.8, data in the form of a 16-bit packet consisting of the addresses and communications messages is routed around the loop. The nodes uses special ICs which has been fabricated as identical custom hybrid ICs, and the transmission speed of the communications

circuit is 1Mbps. In addition, in order to make it possible for the patient lifting arm to be driven by battery power for long periods of time, the entire control system has been constructed using CMOS-IC, thus reducing the power consumption. The power consumption of the entire control system is approximately 15W.

4-2.Sensors and automatic operation sequence

We used two dimensional tactile sensor and opto-electric proximity sensors for the environment sensors needed to achieve automatic operation. As shown in Fig.7, the two dimensional tactile sensor are attached to the entire seat of the hip insertion plate, and are used to confirm the position of the patient on the seat. These are matrix type distribution sensors constructed of pressure conductive rubber sheet and a flexible printed circuit board having stripe electrodes, and the size of the sensing area is 40cm by 40cm. The sensing image of the patient's body are shown in Fig.9. The center of gravity of the pattern is determined in the automatic operation sequence and this is used as the position of the patient.

The opto-electric proximity sensors are reflection detecting type proximity sensing sensors. As shown in Fig.7, these sensors are attached to the front ends of the lifting seats, and they are used to confirm the position of the bed, patient, etc. Fig.10 shows the automatic operation sequence. This sequence is programmed into the general control module. The sequence consists of the following operations.

1. Detection of the bed height.
2. Detection of the patient and insertion plate insertion.
3. Lifting

As shown in Fig.10, detection by the opto-electric proximity sensors is performed in operations 1 and 2 of the sequence. In addition, from the insertion of the seats until the completion of the subsequent lifting and lowering of the patient, the signals from the two dimensional tactile sensor are constantly monitored in order to confirm the presence of the patient on the seats.

It was confirmed that the operations of this automatic operation sequence were executed correctly in actual experiments using a healthy person in place of the patient. The time required for the device to change from the standby mode in a wheelchair type configuration at the side of the bed, lift the patient, and then return to the wheelchair type configuration was less than two minutes.

5.Conclusion

In this report we have discussed the development of a second-stage prototype of a patient lifting arm for a transport apparatus for assisting physically incapacitated persons. In order to achieve a comfortable lifting operation, we have developed a method which uses insertion plates with belts attached to them, and a full-flat type lifting unit is used for the shoulder section in order to further ensure the comfort of the patient. Pneumatic springs are used in both the configuration changing arm unit and the height adjusting mechanism in order to reduce the amount of power required to drive the device. In addition, the positions of the bed and the patient are detected by two types of environment sensor signals, and the control which determines the actions of the control which determines the actions of the device is based on those signals in order to achieve automatic operation. Whole control system is constructed by several local control modules which are installed inside of the mechanism, thus contributing to the realization of a autonomous robot.

We were able to confirm that this second-stage prototype fulfils the functions of a patient lifting arm for use on a patient care robot. However, in consideration of the fact that this device is intended for use in hospitals, we speculate the system must be made even easier to use, such as making the belts easy to replace.

6. Acknowledgment

This work is being done as part of the national research and development program for medical and welfare apparatus of the Ministry of International Trade and Industry's Agency of Industrial Science and Technology.

7. Related publications

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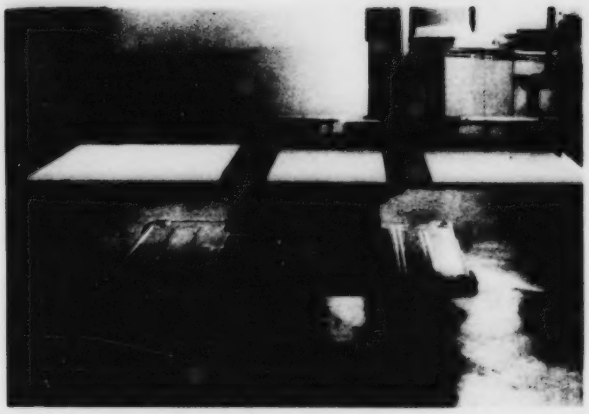
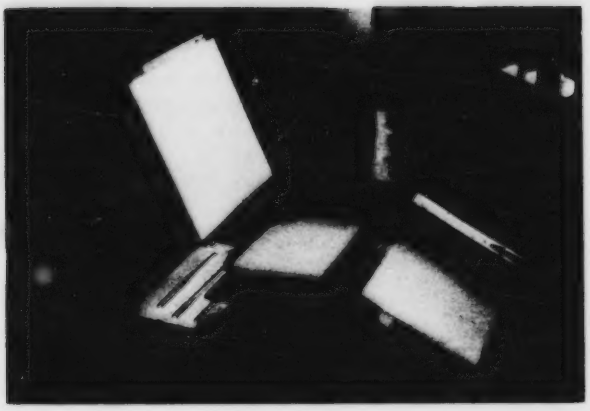
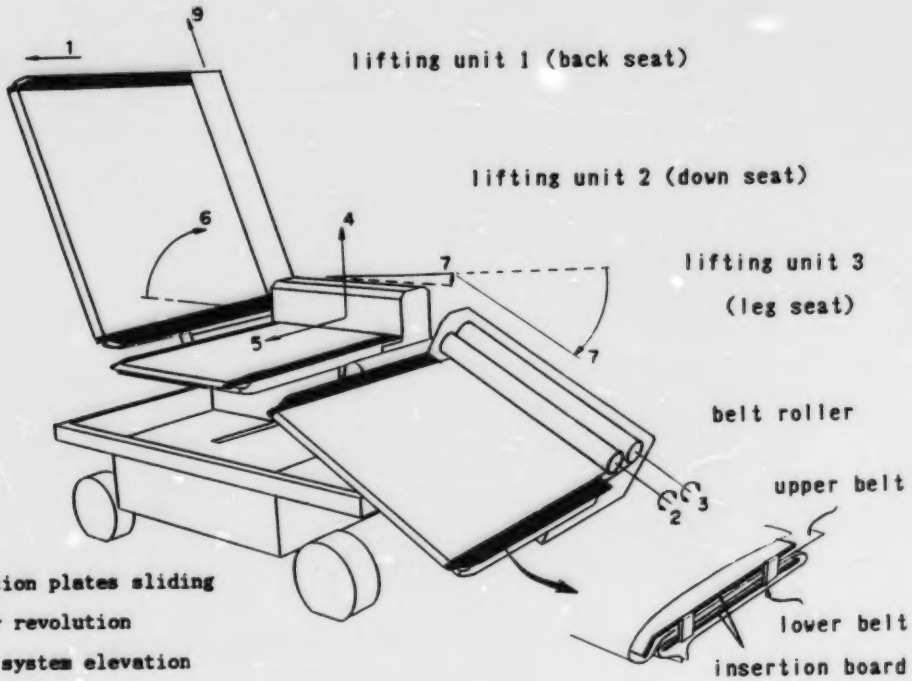


(b)Stretcher type configuration



(a)Wheelchair type configuration

Figure 1 The lifting arm of the transfer supporting system for the physically handicapped



1. Insertion plates sliding
2,3. Roller revolution
4. Whole system elevation
5. Whole system sliding
6. Sit up motion
7. Knee up and Leg down motion
8. Back seat sliding

Figure 2 Construction of the lifting arm

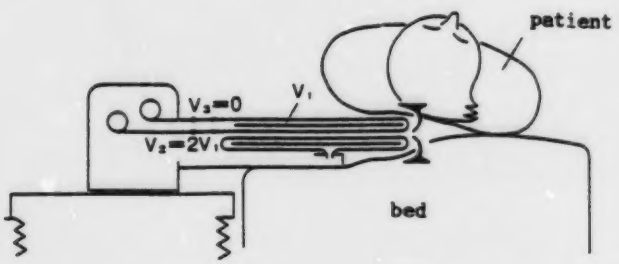
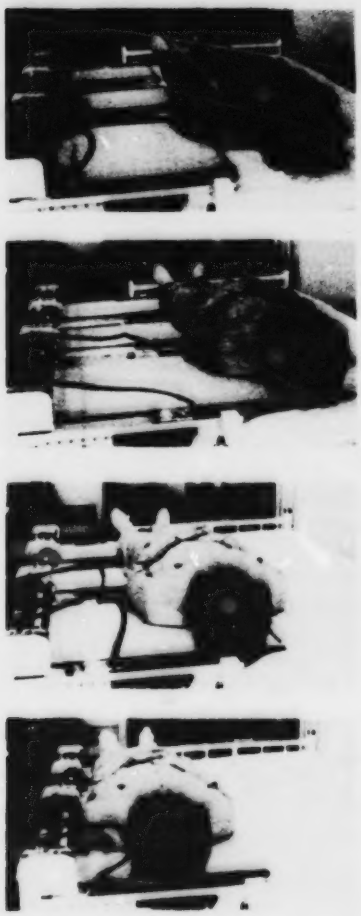


Figure 3 Schematic of the patient lifting principle



(a)

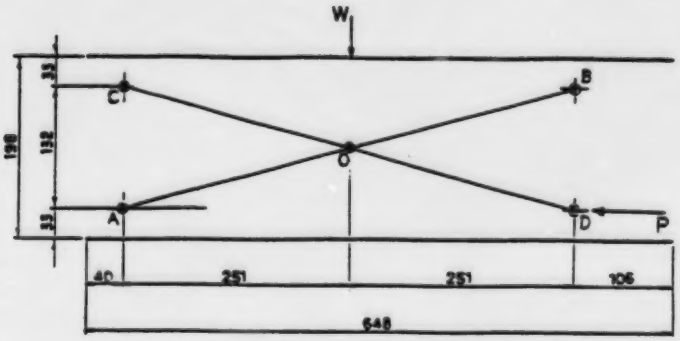
(b)

(c)

(d)

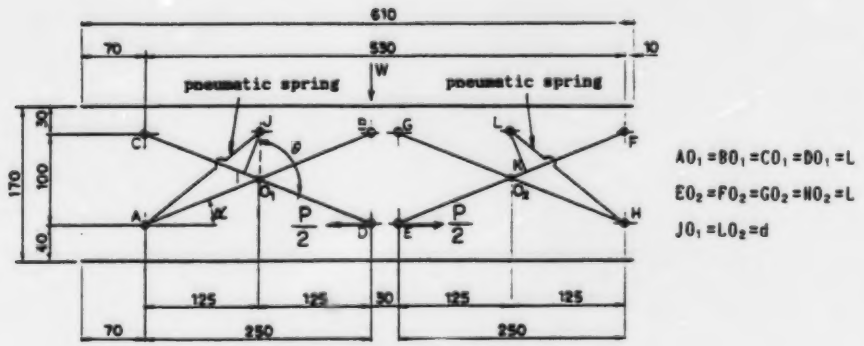
(a),(b) board insertion
(c) board retract
(d) belt rolling up

Figure 4 Sequential photos of patient lifting motion



a single-X link mechanism

Figure 5 Schematic of the height adjusting mechanism first-stage prototype



a double-X link mechanism

Figure 6 Schematic of the height adjusting mechanism second-stage prototype

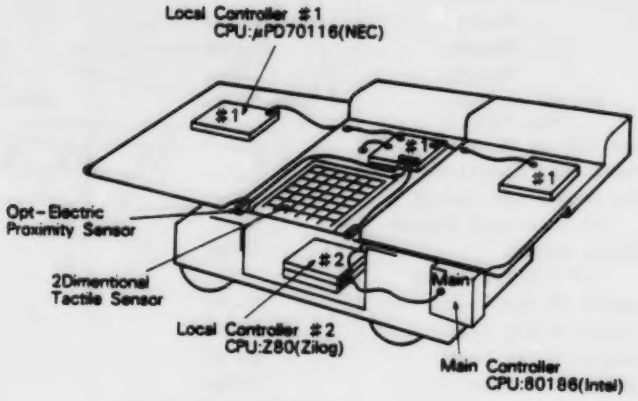


Figure 7 Schematic of the control system

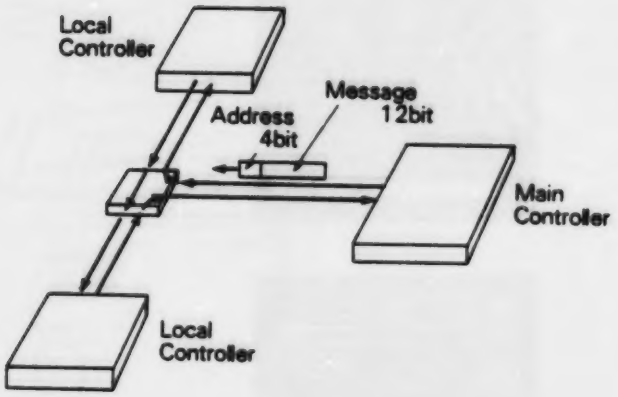
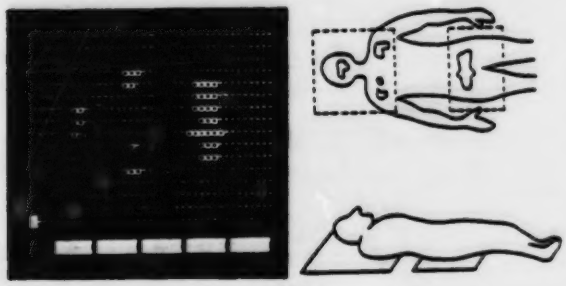


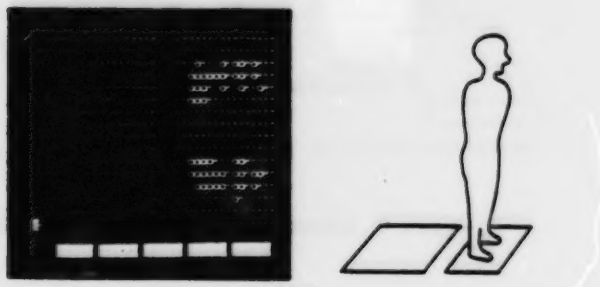
Figure 8 Schematic of the data transmission line

	First-stage prototype	Second-stage prototype
Dimensions and weight		
Width	670mm	650mm
Height	1820mm	1820mm
Weight	160kg	125kg
Height of seat (from floor)	760～980mm	450～600mm
Movement specifications		
Maximum slide amount of insertion plates	400mm	400mm
Slide amount of lifting units	300mm	300mm
Angle of back seat	0～75°	0～70°
Angle of hip seat	0～5°	0～5°
Angle of leg seat	0～50°	0～30°
Amount of slide of back seat	200mm	150mm
Height adjustment stroke	300mm	150mm

Table 1 Specifications of the Patient Lifting Arm

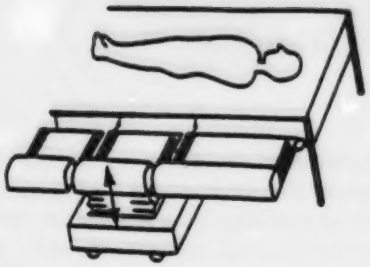


(a)

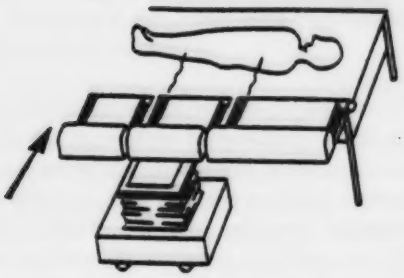


(b)

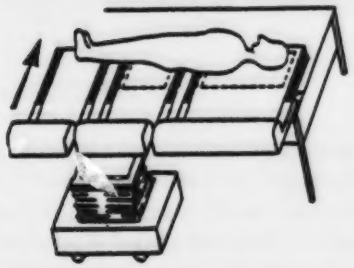
Figure 9 Obtained tactile image
(a) a man laying down on the sensors
(b) a man standing on the sensors



(1) Detection of the bed height



(2) Detection of the patient
and insertion plate insertion



(3) Lifting

Figure 10 Automatic operation sequence

INTELLIGENT PLATFORM FOR HEALTH CARE APPLICATIONS

R. Liscano, D. Green and L.W. Korba
National Research Council of Canada
OTTAWA, Ontario, K1A OR6, Canada

1. INTRODUCTION

Health care costs, especially in chronic care institutions, are very high. Current statistics[1] indicate that the Canadian population is aging and that within the next two decades, our health delivery system will be burdened as a result. There are however many health care facility users who would prefer to live at home where they could enjoy a more independent life-style. Some of these people are in fact able to live at home or in small group homes with the help of part-time nursing. Unfortunately this option is expensive and therefore only available to those who can afford it. The development of an autonomous vehicle to aid the disabled or elderly population could contribute in reducing the escalating costs of health care. This will be true if it can be demonstrated that this technology leads to a shift towards the use of less costly health care facilities. This paper outlines the research direction of a new project at the National Research Council of Canada in developing an autonomous vehicle for the health care area.

The research direction of the mobile robot project at NRC is to improve the mobility of a disabled person by designing a platform that can navigate independently and be able to transport a person to a desired destination. Other possible future extension capabilities could be the ability to dispense medication, to assist with chores, remind the user about daily activities, and/or to perform a monitoring role in order to determine crisis situations. The mobile robot must be able to navigate in a known or unknown area, have the ability to assess its environment so that the desired task can be performed, and be able to locate a human "commander". This paper describes the projects under way within the two research laboratories at the National Research Council of Canada (Laboratory for Biomedical Engineering and the Laboratory for Intelligent Systems) that are directly involved with the mobile platform.

2. HEALTH CARE APPLICATIONS

At present there is an ongoing investigation into applications for the mobile platform where the use of an intelligent navigation device would improve the living conditions of the end user. Meetings with local health care officials indicate that a factor in determining if a person has to enter chronic care is his/her ability to move about. There may be an overall reduction in health care costs if a person could remain in a nursing home institution instead of a much more expensive chronic care institution because of assistance provided by an intelligent mobile device. Three possible applications that have been discussed are: an autonomous wheelchair, an autonomous "auto-porter" that could attach itself to any wheelchair, and an autonomous walker. Of the three applications the autonomous wheelchair is the simplest to implement but may also be an expensive item for the consumer since each wheelchair has to have an independent controller. A more feasible solution is to design an "auto-porter" that could service a set of different wheelchairs in a facility where there would be several patients in wheelchairs. The autonomous walker would have the same autonomous navigation capabilities as well as feedback between the user and the device. All of the three applications have in common the need of an autonomous platform that can avoid obstacles and learn from the environment. Before the applications can be tackled it is necessary to solve the

problems associated with autonomous navigation. At this time we are further exploring the development of an "auto-porter" application.

3. RESEARCH COURSE

In order to address the complex technical issues, several major areas of research and development associated with the control of a mobile platform have been defined. They are:

1. The development of a suitable computer architecture to support real time operation of the autonomous platform.

2. The investigation of suitable control and planning methodologies.

3. The investigation of various sensors and the integration of these sensors.

3.1 Computer Architecture

To achieve an adequate level of performance and safety, a sensor-based mobile vehicle must be controlled by a real-time computing system. Such a system is characterized by an ability to respond in a rapid and predictable way to unexpected events that occur within its environment. In order to be useful in an experimental environment the system must be very flexible. It is important that the computing system be extendable so that sensors can be readily added to or removed from the system. Similarly, it is important that processors can be easily added or removed as the computational demands on the system change.

Research carried out at NRC over the last few years has led to the development of the Harmony* real-time multi-tasking operating system[2]. Harmony has been designed specifically to address the issues of real-time control outlined above and several projects[3,4,5,6,7,8] have already been undertaken at NRC in controlling robot arms using the Harmony operating system. One of Harmony's principal advantages is that it offers transparent multiprocessing. Harmony is an open, expandable system which supports the custom interfacing of peripherals.

The multi-tasking concept used in Harmony is an abstraction which encourages the functional partitioning of a real-time control problem. Typically, tasks are assigned specific resources to control and functions to perform. Tasks are dynamic entities that can be created and destroyed as required. They communicate and synchronize through a message-passing mechanism. In the development of a typical application, many tasks are defined to perform the various functions required by the system. The nature of the inter-task communications is also specified. At compile time, the tasks are physically allocated to specific processors. If necessary, processors can be added and tasks reallocated to achieve better load balancing.

Figure 1 shows the system being configured for the mobile robot which is based on 68020-based single board computers operating on the VMEbus. A separate bus architecture based on the VSB[9] subsystem bus will

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be used for communicating with the various sensors that are being developed. This will facilitate the addition of sensors to the system.

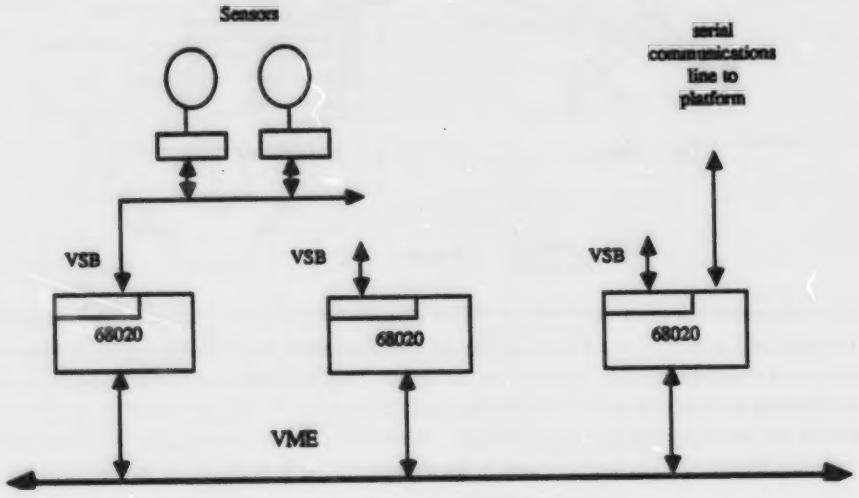

Figure 1.

Software development for the system is supported by a network of Apple Macintosh computers.

3.2 Control Methodology

Figure. 2 is a sketch of the computer controlled platform that was purchased to facilitate the research into autonomous navigation. The platform has a synchro-drive mechanism where the three wheels are synchronously driven or steered. This drive mechanism has the advantages that the body does not rotate with the vehicle and therefore the rotational mass of inertia is lower than a vehicle in which the whole body rotates, also it gives the vehicle a zero drive turning radius capability. The disadvantage is that the body of the vehicle has no front or back and for that reason there is a protruding vertical that rotates with the wheels. The syncro-drive mechanism has been implemented using direct drive shaft coupling minimizing the errors that can be encountered through slip and misalignment inherent in using chains or belts for coupling.

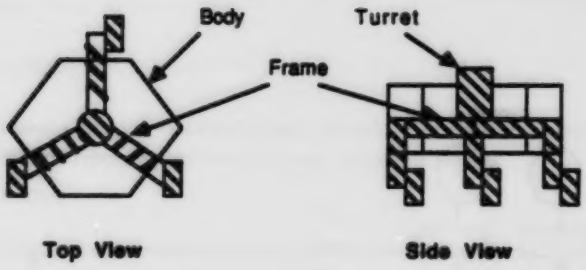

Figure 2

A hierarchical control structure consisting of four layers is being implemented to control the platform. We are using the work of J. Albus[10] as a framework for the composition of the layers of controller. Figure 3 illustrates a general composition of the levels of the controller. The Hi module is a transform corresponding to the planner that responds to the commands Ci and the feedback information Fi. The Mi module is memory of previous sensory patterns and the right pattern to use is instructed in the command Pi. Information Ri is used by the sensory perception module Gi. The memory used in the module Mi can be modified by any external occurrences via Xi.

Unlike the implementation by J. Albus only the sub-controllers of the sensors and motors will be time based, the real-time events will be controlled by the messages Ci that are being sent to the command interpreter Hi and information in the feedback loop Fi. Implementing the controller in a hierarchical fashion has the advantage that the design can be divided into clearly defined levels of command decomposition and sensor data composition. Design of the controller can then proceed from the bottom layer up to the top.

The design of the bottom layer is dependent on the platform configuration while the layers above this level are independent of the platform structure. Part of the bottom layer of control has already been implemented in the platform by the manufacturer and consists mainly of the controller for the motors with an interface to the outside world via a serial communications line. Presently we are designing the tasks that will allow us to interface Harmony to the platform controller and control the platform issuing velocity commands.

The Level 2 controller is being implemented and consists of the design of a trajectory generator that controls the velocity of the vehicle so that a smooth transition, as shown in figure 4, can be performed between two desired straight line paths. Included in the Level 2 is the sensory perception of a nearby object from the ultrasound sensors. Our immediate goal is for the vehicle to traverse along desired straight line paths with the ability to smoothly move from one path to another and stop if an obstacle has been detected.

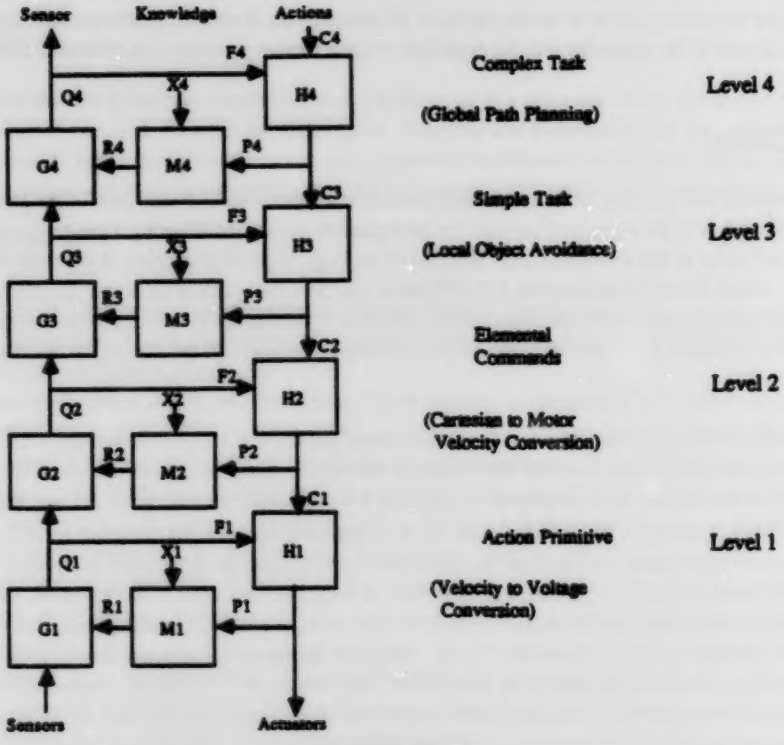

Figure 3.

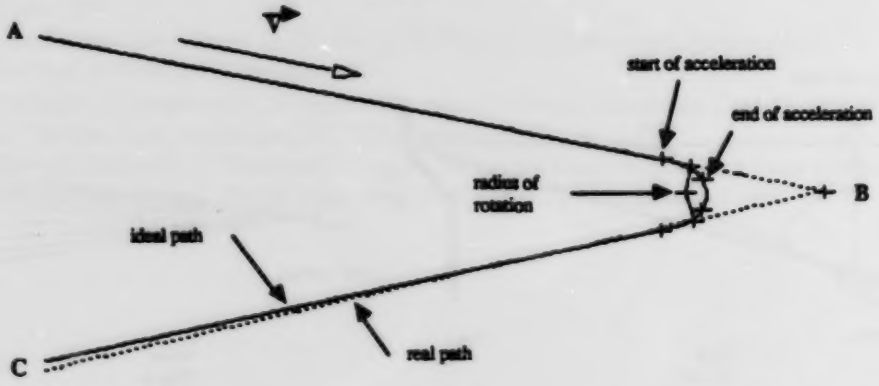

Figure 4

The Level 3 controller will follow upon the implementation of Level 2. This level will be capable of creating paths for the robot in order to avoid objects in the desired path of motion. Some research topics that are relevant in the design of the controller are: the capability of error recovery, sensor data representation and sensor integration.

3.3 Sensor Design

The platform will be fitted with twenty-four ultrasonic sensors spaced evenly around the girth of the platform. Each bank of eight ultrasound sensors can be separately controlled allowing a pre-programmed firing sequence for each bank to fire simultaneously. Because of the large angle of dispersion of the beam emitted from the ultrasound sensor, about fifteen degrees, it is difficult to calculate the width of an object detected by the sensor. Also ultrasound signals have the characteristic that most materials act as specular reflectors therefore the power of a reflected signal that is greater than one half the dispersion angle off the axis of the beam will be very low or nonexistent.

To overcome the problems associated with the ultrasound a low cost laser slit scanner is being developed for the purpose of sensing objects that may be avoided by the vehicle along the path of motion. It is intended that this scanner will reside on the turret section of the platform that turns with the wheels, in this way it will point in the forward moving direction of the platform at all times. A previous laser scanner designed at NRC[11] has been very successful and experience from this has led to the simple preliminary design shown in figure 5. The ranging calculations are based on the fixed geometric arrangement of the sensor as shown in the top view. The vertical slit of light that comes out of the laser diode, as shown in the side view, is projected straight ahead and any reflections of an object are captured by the CCD camera. The reflected light appears as a horizontal line on the CCD camera and the sensor can be calibrated so that the position of the reflection on the CCD array corresponds to range. At present the system is configured only to return the closest point of the object that the laser slit incidents upon. The whole unit, camera and laser diode, is rotated in a horizontal plane so that a scan of about ninety degrees in front of the vehicle is obtained.

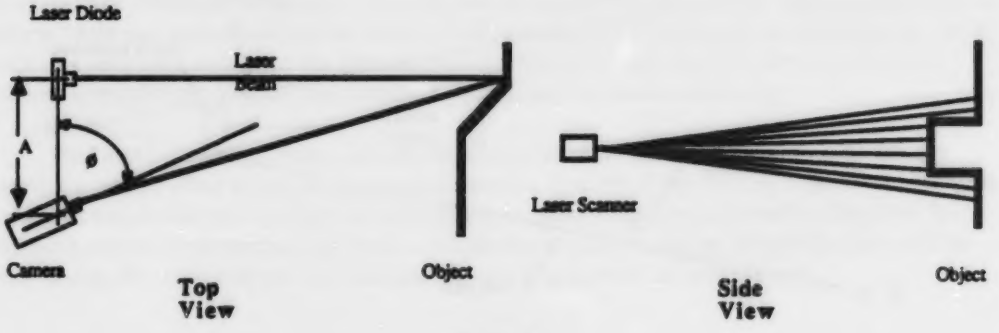

Figure 5.

Concurrent with the sensor development for ranging applications another project is investigating types of sensors capable of localizing humans. These consist of the combination of sound detecting, heat detecting and

motion detecting sensors.

SUMMARY

We feel that the technology required in an autonomous mobile robot may serve to improve the quality of life for the disabled and aged. To aid in establishing our directions and in disseminating this technology we have established contacts with a user community and manufactures of mobile devices for the handicap. We hope to see further collaboration with these organizations once we have successfully demonstrated the technology.

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INVESTIGATING ARTIFICIAL TACTILE SENSING FOR ADVANCED MEDICAL ROBOT SYSTEMS

P. DARIO, M. BERGAMASCO, A. SABATINI, G. BUTTAZZO
Scuola Superiore S. Anna, Pisa
and
Centro "E. Piaggio", University of Pisa, Pisa, Italy

1. INTRODUCTION

Possible applications of advanced robot technology to the biomedical field include rehabilitation, prosthetics, orthotic telemanipulation, stereotactic surgery and medical laboratory automation (1)(2)(3). The increasing cost of medical care and the difficulty to find trained paramedical personnel, may justify research efforts aimed also at developing robotic systems capable of executing autonomously simple diagnostic and therapeutic procedures, some of which involving the manipulation of body parts. However, a major obstacle to the practical achievement of this goal is the inability of present robots to sense and control contact forces. Actually, whereas the first safety principle of industrial robots is to prevent the machine contacting people, medical robots are intrinsically required to interact with people, often in intimate ways such as feeding and eye surgery (4).

Based on this premise, we have elected to investigate the feasibility of a robotic approach to the automated execution of complex medical tasks requiring the manipulation of soft biological tissues, with the goal of either performing useful therapeutic operations (e.g. massages), or detecting by touch possible pathological situations in order to formulate diagnoses. To this aim, we have devised and implemented a simplified testbed consisting of an articulated finger with "internal" and "external" sensors, and a control architecture specifically intended for providing the robot system with the ability to palpate body parts (5)(6).

2. THE ROBOT SYSTEM

The robot system consists of three blocks, as shown in Fig. 1: 1) a high-level "expert" system, at the top of the control hierarchy (this "expert" decides the overall diagnostic strategy, consisting of a sequence of sensory-motor acts, called "tactile subroutines" and coordinated at the intermediate control level; the "expert" also processes and interprets the data provided by the finger sensors); 2) a middle-level block that manages the execution of tactile subroutines; and 3) a low-level block comprising hardware components: a tendon actuated four-degree-of-freedom finger with sensors, motors and drivers, preprocessing electronic units, and other sensing devices (7).

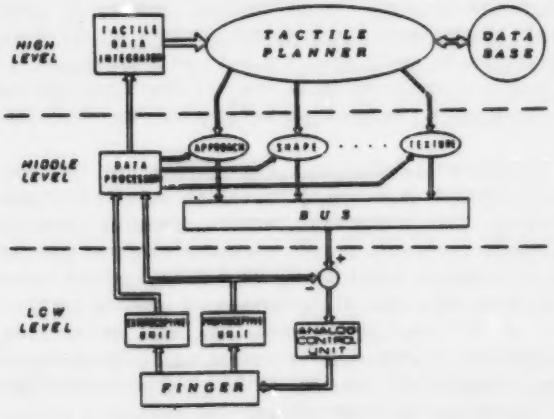

Fig 1: Hierarchical robot system architecture (from (7)).

The exploratory finger, that imitates functionally the index finger of the human hand, is composed of four rigid links connected by hinge joints. Compared with a previous version of the finger we described in other papers (5)(7) (and that we have actually used in some of the experiments described in this paper), some important modifications have been devised for the sensors and the actuators in order to optimize finger performance during the delicate sensory-motor procedures we intend to investigate. A preliminary description of this multisensor fingertip has been presented in (8).

The structure of the fingertip has been designed to include a 6-axis resultant force/torque sensor at the base, an array of piezoelectric tactile sensors at the cover, and a few piezoelectric polymer ultrasonic (US) range transducers located in various sites of the fingertip surface.

A seeming dilemma that we tried to solve is between the need for accurate force sensing and the interest for local information on contact features. The solution we propose is to assign those two sensing roles to distinct devices: the force/torque sensor is purposely designed to accomplish the sensing functions required for finger low-level compliant motion control, while the tactile sensor array has the primary function of sensing local object features mainly for perceptual purposes. The US range transducers also contribute to the finger ability to comply with variable environmental conditions by providing not only relatively long-range information on the presence of objects, but also middle- and short-range data usable for reconstructing some geometrical object features. Thus, the range sensing array allows controlling the approach motion of the finger to an object as well as the extraction of "pretactile" non contact information on the object through appropriate exploratory movements.

Let us now briefly consider the functioning of each individual sensor, starting from the force/torque resultant sensor.

In general, a force sensor is a device which measures, in a particular coordinate frame, the six components of the "generalized force" vector (i.e. three pure forces and three torques) that is exerted through the sensor itself during contact. This task is usually carried out by measuring the deformation that the applied load originates in a suitable mechanical part of the sensor. So far, most force sensors have been developed to fit the wrist of a robot arm; thus, specifications concerning size, weight, robustness, etc., differ considerably from those required for a fingertip force sensor. A fingertip force sensor has been recently developed for being incorporated in the fingers of the Stanford/JPL hand (9). Although this sensor turned out to be rather efficient, it is complex to fabricate and delicate; a simpler structure may be desirable in order to integrate the force sensor and other sensors in the same fingertip.

We devised an extremely simple, miniaturized sensor configuration in which the deformations of a thin walled cylinder originated by the contact force are transduced by the minimal number (i.e. six) of strain gauges (10). In the theoretical analysis that supports the design of this optimized force sensor, particular attention has been devoted to render the linear system of equations that relate strain measurements to the unknown components of the external load as well conditioned as possible.

It is also worth observing that a force sensor mounted in the fingertips of a robotic hand can be useful not only to detect the six components of the resultant contact force vector (thus being immediately useful for the force-servo loop control), but also, provided that some reasonable hypotheses are verified, to calculate the point of application and the direction of the resultant contact force vector (thus providing information usable also for perceptual tasks). We have verified experimentally that a simple and cheap foil strain gauge-based force sensor located at the base of a spherical fingertip having 26 mm diameter can detect forces as small as 0.1 N with an accuracy of 2 %; the sensor also allows calculating the location of the point of application of the resultant contact force with an error smaller than 1 mm in a force range of 0.1 - 30 N, as well as estimating the friction coefficient between the fingertip cover and an object.

One of the above mentioned hypotheses is that only pure forces (no torques) are exerted through the fingertip contact area. Such point-contact is somewhat unrealistic in the frequent case of very compliant fingerpads (a convenient solution for achieving better grasping stability). Furthermore, fine manipulation and palpation may require extracting very detailed information on local contact, both in terms of force sensitivity and of spatial resolution. Skin-like tactile sensors distributed over the fingertip pad and capable of resolving the local distribution of contact forces may effectively integrate the force sensor for the control of delicate manipulation, as well as provide specific information on geometrical and other physical features of the objects belonging to the work environment.

The tactile sensor we have fabricated has an anthropomorphic configuration, since it mimics functionally, even if not morphologically, the human finger-pad skin .

The multiple sensory capabilities of this tactile sensor result both from the disposition of different sensing elements in a compliant, conformable sensor structure, and from controlled motor acts intended to elicit specific tactile stimuli. The structure of the fingertip tactile sensor is depicted in Fig.2 .

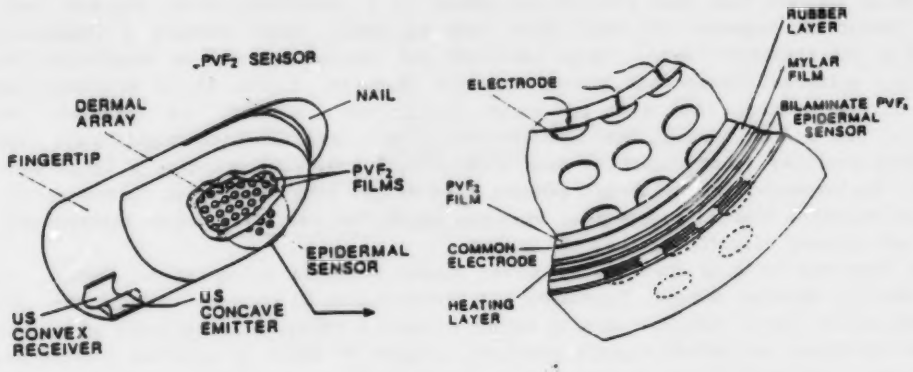

Fig 2: A scheme of the fingertip skin-like tactile sensor showing a close-up view of the layered sensor structure (from (13)).

The sensor comprises a superficial ("epidermal") sensing layer, an intermediate compliant layer and a deep ("dermal") sensing layer. Both sensing layers are made out of ferroelectric polymer (polyvinylidene fluoride or PVF2) material, while the compliant layer is natural rubber.

The dermal sensor, which comprises 128 sensing sites, is intended to mimic conceptually the role of the slowly adapting (SA) skin receptors, that are very sensitive to fine spatial details, while the epidermal sensor, comprising, at the present stage of implementation, only 7 sensing sites, simulates the function of the quickly adapting (QA) receptors, which preserve only the coarsest spatial details of an indenting profile (11).

The pattern of dermal sensing sites is defined by circular electrodes (diameter 1.5 mm, center to center spacing 2.5 mm) obtained on the surface of a 21 mm diameter cylindrical plexiglass frame and of a hemispherical tip on top of it (the "fingertip"). A 110 micron thick PVF2 film is conformed and bonded to the fingertip. The electrical charge generated by pressure or temperature variations is transferred capacitively to the pattern of electrodes, and sent to a dedicated electronic unit for signal preprocessing.

The intermediate rubber layer has the twofold function of providing some compliance to the sensor and of shielding the dermal sensors from rapid temperature transitions (a 1.5 mm thick rubber layer introduces a time delay of about 1 second between the detection of thermal signals in the epidermal and dermal layers) (12).

The epidermal sensor is made out of 80 micron thick PVF2 film. The pattern of 7 circular sensing sites (diameter 1.5 mm, center to center spacing 2.5 mm) is obtained by vacuum depositing aluminum on the PVF2 film; then the electroded locations are poled selectively by applying a strong electric field .

The epidermal sensor, located in the central area above the dermal array, comprises an inner graphite ink-based resistive layer (100 micron thick, 500 ohm resistance), and it is located in the central area above the dermal array. When connected to a power supply, the resistive layer becomes a heat source and establishes a temperature gradient between the fingertip and other objects at room temperature. The heat flowing from the fingertip to a touched object, that depends on the thermal properties of the object as well as on contact conditions, is detected by the epidermal sensor through the pyroelectric effect.

From a conceptual viewpoint, the central area of the tactile sensor, comprising the epidermal sensor and those dermal sensors directly underneath, represents the "tactile fovea" (i.e. the area of maximum perceptual acuity) of the whole transducer. An important subset of a possible sensory-motor sequence aimed, for example, at feeling an arterial pulse should therefore involve both orientating the fingertip in order to put the tactile fovea on the radial artery, and finely adjusting the fingertip position and contact force in order to optimize the intensity and the waveform of the pressure pulse sensed by the tactile receptors and "perceived" by the high level controller.

The epidermal and dermal sensors have distinct, but closely correlated, sensing roles. Being made of the same material, they are both sensitive to strain and temperature: however they have different mechanical and thermal boundary conditions. Because of its mechanical constraints, the dermal sensor works predominantly in thickness mode: thus it measures primarily the normal components of the contact forces acting on each sensing site. The amount of cross-talk between the dermal sensing elements is very small: hence, these elements provide "crisp" tactile images of the touched feature, with negligible blur.

The dermal sensors have good sensitivity (about .01 N resolvable force, maximum load about 40N) and linearity (about 1%, between 0.01 and 2.56 N peak to peak), small hysteresis (basically only the one introduced by the elastomer layer), large bandwidth and limited response to temperature variations.

The thin epidermal sensor has almost opposite features. First, it is extremely sensitive to any variation of the contact (and even proximity) conditions. In fact, the epidermal sensor feels the proximity of hot bodies through the pyroelectric effect, and exhibits significant responses when it touches sharp profiles (that determine deep indentations and, consequently, a large strain in the thin PVF2 film). Furthermore, the epidermal sensors also detect roughness, when rubbed gently on the object surface, and material thermal properties, when heated by the resistive layer incorporated in the sensor structure and pressed slightly against the object.

It is important to note that the epidermal sensor responds primarily to strain, while the dermal sensor primarily measures stress. Together, both sensors can be used to measure the "hardness" of the object material. In fact, when the tactile sensor presses a relatively flat part of an object, the ratio between the epidermal and dermal signals provides a figure of merit of material elastic properties.

It is also possible to use piezoelectric polymer-based curved transducers to emit and receive US waves in air. We have designed an array of curved, alternatively concave and convex, transducers using 25 micron thin PVF2 film. Each concave element emits a focused US beam, while each convex element forms a wide acceptance angle US receiver. The easy conformability of the PVF2 film allows varying the shape (hemispherical or hemicylindrical) of each element, its dimensions and the pitch of the array. US transducers with a small radius of curvature (about 1-1.5 mm) emit a beam focused at a short distance (usually 10-30 mm) for high resolution, short range exploration, while larger radius (3-4 mm) transducers focusing at longer distances (50-120 mm) are used for low resolution, long range sensing.

All the sensors incorporated in the fingertip (the 6-axis resultant sensor, the tactile sensor and the US transducer) are connected to dedicated amplifying and multiplexing electronic units, and to the control computer (a DEC Micro PDP11/73), that processes the signals detected by each sensing element.

3. PALPATORY PROCEDURES

The design philosophy we have followed in the definition of the overall system architecture is based on the assumption that, in order to investigate artificial tactile perception in automata, it is convenient to separate conceptually sensory-motor functions from perceptual functions. The same approach can be followed for replicating, for instance, the skilled behavior of a physician searching by palpation the radial artery pulse at the wrist or a malignant nodule in the breast of a patient. In our robotic system, the execution of appropriate sequences of exploratory sensory-motor acts aimed at providing the high-level controller with signals that can be analyzed and interpreted as originated by a pulsating vessel or by a hardened region underneath the skin, can be managed autonomously by the intermediate control level. Based on this approach, the execution of exploratory sequences ("subroutines") requires only a set of synthetic instructions from the high-level controller, whose "attention", instead, is almost completely engaged by the analysis of the information provided by the cutaneous sensors.

We have tested satisfactorily this conceptual scheme in the cases of a subroutine ("PULSE") aimed at sensing and analyzing the radial artery pulse waveform at the wrist (13), and of a subroutine ("PALPATION") intended for controlling the robot finger to sense hardened regions in a soft environment mimicking woman's breast (14).

Consider first the case of wrist artery sensing. According to the present simplified approach, an appropriate sequence of exploratory sensory-motor acts aimed at providing the high level controller with a signal related to the arterial pulse of the patient, should be managed autonomously by the intermediate control level. A block diagram of the subroutine "PULSE" is shown in Fig. 3.

As pointed out in the introduction, a fundamental aspect of any robotic tactile procedure is the ability to control compliant motion. In (15) we have proposed a method for controlling force and position during the exploratory movements of the robot finger. This method utilizes the signals provided by the dermal tactile sensors to calculate the common normal direction (n) to the contact point between the fingertip and the explored object (in our case, the patient's wrist surface), and the tangent plane to the same point. The high level controller commands the finger to move a step of length L along a direction t belonging to the tangent plane, and to simultaneously exert a given force F on the object along the normal direction n. Both normal and tangent directions are calculated, in the fingertip reference frame, by the coordinate transformation unit (7). The tangent unit vector is multiplied by L and the result applied to the Jacobian inverse matrix J^{-1}, that provides the angular increments dQ of each joint. The sum of those increments is sent to the low level control as the nominal position command Q. The normal unit vector is multiplied by F and the result applied to the Jacobian transpose matrix J^{T}, that provides the nominal joint torque vector T. A is the actual joint position vector, measured, in the

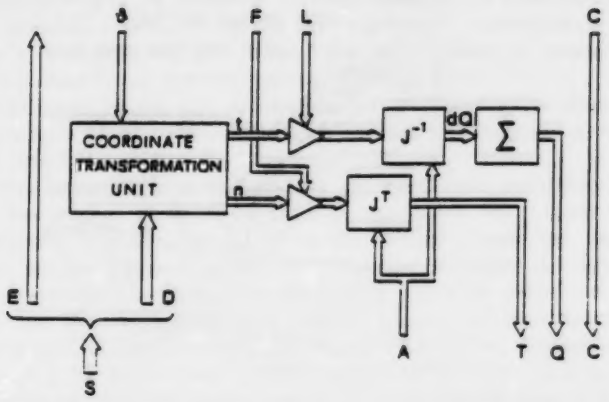

Fig. 3: Block diagram of the subroutine "PULSE". The pulse signal E detected by the epidermal sensors in the tactile fovea by-passes this intermediate control level and goes directly to the high level unit (from (13))

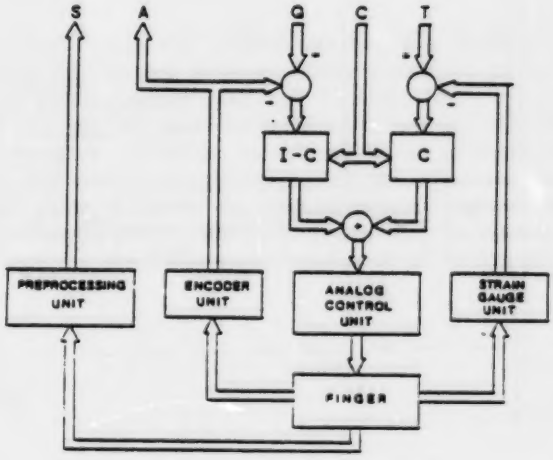

Fig. 4: Low level control. Finger stiffness is adjusted by the high level controller by setting the value of C according to the task to be executed. I is the identity matrix (from (13)).

joint space, by the incremental encoders. C is a diagonal compliance matrix that controls the stiffness of the finger movements and acts as a balance factor between the torque command and the position command.

The actual committment of the high level controller during the execution of the subroutine is limited to set L, F, C and $\dot{\theta}$ (the direction of finger motion in the plane tangent to the contact point). Hence, most of the processing resources available at the top control level can be focused on the perceptual task, rather than being involved in the control of the sensory-motor procedures.

The role analysis of the different components of the robot system elucidates the system design approach we have followed. At the low control level, schematically depicted in Fig. 4, the position and torque control of the finger is accomplished in the joint space, where each joint can be controlled independently and directly.

In this scheme, which corresponds to the "low level" block in Fig. 1, it is worth observing that, while the actual joint torque vector G measured by the strain gauge sensors is used only in the force feedback loop, the actual joint position vector A is used not only in the position feedback loop, but is

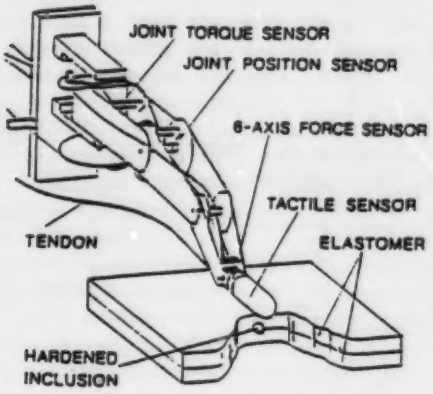

Fig. 5: The anthropomorphic finger sensing a hardened inclusion in a soft environment by palpation (from (17)).

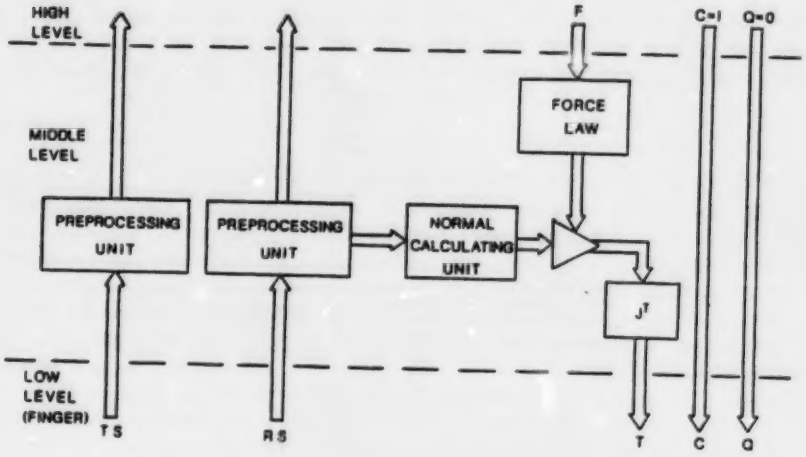

Fig. 6: Block diagram of the control system for the execution of the subroutine "PALPATION" (from (14)).

also sent to the upper control levels for further processing (for instance it may be used to reconstruct the shape of an object). The signal detected by the tactile sensors (S), instead, is sent directly to the middle control level, where the dermal (D) and epidermal (E) signals are processed separately. The dermal signal is used for executing "PULSE", while E is of immediate concern for the high level, perceptual control system. This "direct" connection of the epidermal sensory receptors of the fingertip tactile fovea with the high level controller could be regarded as a sort of artificial analog of the projection between large portions of the somatosensory brain cortex and the fingertip sensory receptors in humans.

As a physician moves his/her finger almost unconsciously on the patient's wrist, while his/her perceptual capabilities are fully engaged in the effort of capturing the features of the pulse perceived through the fingertip cutaneous receptors, the high level controller commands finger movements by setting the values of L, F, θ and C, for "PULSE", according to significant parameters (i.e. pulse amplitude and the evidence of the dicrotic notch) obtained by processing the pulse signal detected by the epidermal tactile sensor pressed on the radial artery.

Consider now the case of the subroutine "PALPATION", intended for controlling the robot finger to sense hardened regions in a soft environment, as shown schematically in Fig. 5. Breast palpation is based on the assumption that, if one or more hard regions are embedded in an environment of softer tissue, and

the skin of the finger or of the palm, which forms the boundary of the environment, is pressed with uniform stress on it, the surface will be deformed in such a way as to conform to the underlying hardened regions. In other, more precise, terms, regions of different viscoelastic properties change the stress-strain relations on a boundary (in our case, the skin), and by measuring these stress-strain relations, information on the underlying tissues can be obtained (16).

Although the robot finger can carry out quite complex exploratory procedures by finely adjusting position, orientation and contact force, "PALPATION" is intended to command a very simple sensory-motor sequence, as illustrated in the block diagram of Fig. 6.

At the low control level, contact force is detected by the 6-axis resultant force sensor (RS). After appropriate preprocessing, the signal from RS is used to calculate the intensity, point of application and orientation of the resultant contact force. As in the present case the phantom breast has a flat surface, the common normal to the fingertip and the phantom surface is sufficient to appropriately command the finger. Finger operation is controlled through a suitable force law, adjusted at the middle control level after that it has been triggered by a command signal (F) sent by the high level controller. Usually the force law, converted at the intermediate level into joint torque command (T), through the transposed Jacobian matrix, J^T, is sinusoidal. Furthermore, as we use here a pure force command, the motion command, Q, is set to zero; the compliance matrix C, that can be used for adjusting the stiffness of the finger, is set to I (identity matrix).

The signal detected by the tactile sensors (TS), the one that contains the actual information on the strain at the surface of the phantom breast, is sent, after preprocessing, to the high level controller for further analysis.

4. EXPERIMENTAL RESULTS.

In order to test "PULSE" the finger was pressed against the wrist of a healthy subject with an adjustable contact force, while exploratory movements were commanded in order to optimize the pulse waveform signal detected by the tactile sensor (see fig. 7 left).

The waveform was perceived as optimal when: a) pulse amplitude was the largest, and b) the dicrotic notch was clearly detectable. The first condition is related to the position of the finger on the wrist, while the second depends (for the same finger position) on the pressure exerted by the finger on the artery. The search for optimal pulse waveform was carried out through a two-step procedure, in which finger movements and force adjustments were commanded sequentially. An example of pulse waveform detected by the PVF2 sensor when the fingertip exerted a contact force of 1N on the wrist of a healthy patient is shown in Fig. 7 right.

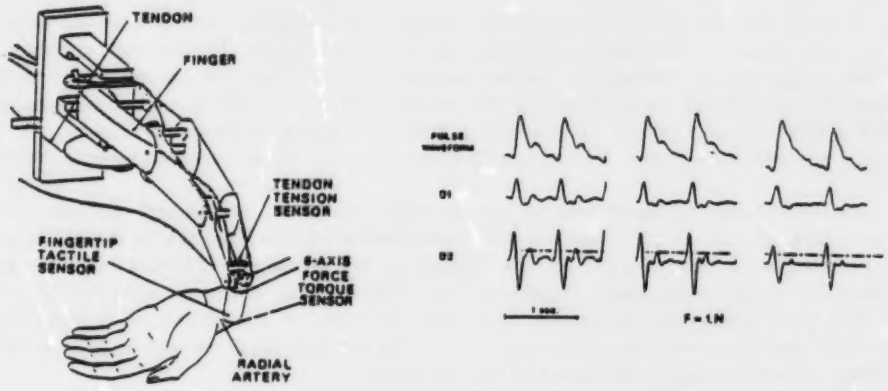

Fig. 7: Sketch of the robot setup for sensing the arterial pulse (left). The pulse waveform recorded at the same wrist location, with the calculated first (D1) and second (D2) time derivatives, allowing to detect the dicrotic notch, are also shown (right) (from (17)).

The subroutine "PALPATION" was tested as shown in Fig. 5. A phantom breast was prepared with two layers of high density urethane rubber (Young's Modulus Y = 10 MPa, in the small deformation range). A few spherical inclusions, having the same diameter (10 mm), but made out of different materials (high density styrofoam, with $Y = 1.5 \cdot 10^3$ MPa, and stainless steel, with $Y = 2.1 \cdot 10^5$ MPa), were embedded

between the two rubber sheets (each 10 mm thick). The phantom was posed in the working area of the robot finger, and the finger was then commanded, through the subroutine "PALPATION", to press the phantom on and around the areas in which the spheres were embedded. The typical imparted force law was sinusoidal, with frequency 1 Hz, offset force 2 N, peak-to-peak force 1 N. After each palpation test, the finger moved a 1 mm step laterally. The peak-to-peak amplitude of the signal detected by the tactile sensor element in contact with the phantom breast was recorded during each palpation procedure. These values were used to draw the diagrams of Fig. 8, which show a clear peak in correspondence with the center of the spherical inclusion, and a marked dependence of the signal on the material of which the inclusion was made out. Results predicted by an "ad hoc" developed model of the system viscoelastic behavior are also reported (14).

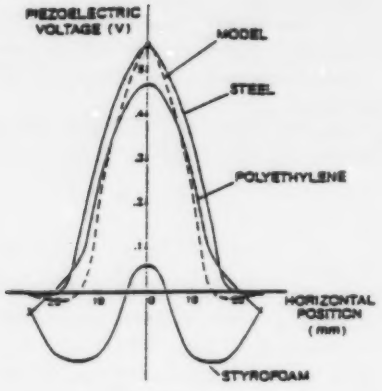

Fig. 8: The finger sensor output for different spherical inclusions (diameter = 1 cm, depth = 1 cm) (from (17)).

5. CONCLUSIONS

The problem we have elected to investigate is susceptible of being extended to cover a variety of aspects related to the robotic assistance to the disabled. In fact, it is our opinion that robot technology will have a significant impact on health care only after that the hardware and software tools required for a robot to be capable of controlling the contact force it exerts on the patient body will be available. In this context, the ability of palpating soft biological tissues is a sort of basic skill that every real "biomedical" robot (for instance a "rehabilitative" or a "surgeon" robot) should possess (17).

A number of problems remain to be solved in our approach. Part of them relate to the reliability of the mechanical structure of the finger, and to the performance of the tactile sensors. Hopefully, both aspects will be improved in a new version of the finger we are presently fabricating. We also plan to develop soon a complete articulated hand incorporating fingers with features similar to those of the prototype finger described here, and to attach this end effector to the wrist of a PUMA 562 Mark III robot manipulator that has been recently installed in our laboratory. This should allow us to extend our analysis to the study of more complex manipulation procedures.

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VOICE CONTROL IN ROBOTICS - PRINCIPLES AND SELECTED APPLICATIONS IN MEDICAL AND REHABILITATION AREAS

Klaus Fellbaum,
Institute of Telecommunications, Technical University of Berlin, Einsteinufer 25, D-1000 Berlin 10, West Germany

1. INTRODUCTION

Human's most important form of communication is speech. Thus it is evident that he wants to have speech as a communication form in the man-machine dialogue as well.

However, we are far away from a human-like speech dialogue. The main problem is not the realization of 'speaking machines'. In most of the practical applications, above all in robotics the vocabulary, which has to be given out, is limited to some words or phrases. This kind of speech material can be produced easily by digitized and specially coded human speech /3,4/.

The bottleneck is speech recognition. Continuous forms of recognition are in the state of research at the moment. On the other hand, for many applications (in the robotic and rehabilitation area as well) restricted forms of speech input are sufficient and very useful.

This paper roughly describes principles of speech processing and it discusses advantages/disadvantages and limitations. It will be explained why the man-machine dialogue by voice must be regarded strictly in connection with its special application or task.

2. SPEECH DIALOGUE COMPONENTS

Fig.1 shows a preliminary classification of the man-machine communication which will be used in this paper. If the machine speaks we have speech output. Otherwise, if the machine receives speech, we call it speech input.

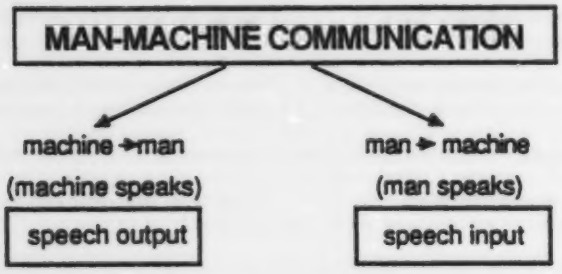

Fig. 1: Classification of the man-machine communication

2.1. Speech output

For most of the technical applications we only need a limited vocabulary. The system has to pronounce error, alarm or confirmation messages, control instructions, standardized questions, phrases, help functions a.s.o. An interesting application in the field of rehabilitation is the 'acoustic keyboard' for the blind, where each pressed key is spoken, thus allowing the disabled to control what he has pressed and possibly to learn typewriting.

A limited vocabulary can be spoken by a human and stored in a memory. From here it can be replayed, and thus we call such a system 'replay system'. Another term usually applied in the American literature is 'voice store and forward' system.

The speech of replay systems sounds naturally and its quality depends on the coding technique and the bit rate. On the other hand the bit rate influences the required storage capacity. To give an impression of today's state of the art, on a standard hardware board we can store about one minute of high quality PCM speech. With a little degradation of the speech quality, and, using a delta modulation technique we have about two minutes of speech. Finally with the aid of a special speech compression technique, called *Linear Predictive Coding (LPC)*, we can store speech of about half an hour with acceptable quality.

In some cases we need an *unlimited* speech vocabulary. As an example, we have developed a 'reading machine' for the blind, which transforms written text into speech /1/. As any kind of text may come into question, it is impossible to record it in advance. We therefore use another technique, called *speech synthesis*. Its principle will be shortly explained here.

Speech is concatenated from short phonetic elements like phonemes, diphones (double phonemes) or others. It can be shown /1, 4/ that a restricted number of these phonetic elements is sufficient for generating an unlimited speech vocabulary.

Although the phonetic elements are taken from natural speech, the generated speech sounds synthetically. The reason is twofold: firstly, the various sound transitions which are typical for natural speech are replaced here by more or less standardized deterministic transitions. Secondly, the phonetic elements are neutral, i.e. they have no stress or speech melody. These so-called 'prosodic elements' must be added artificially - a problem which is just in the state of research.

2.2 Speech input

There are various kinds of speech input. For this reason it is useful to express the classification by three questions (fig. 2):

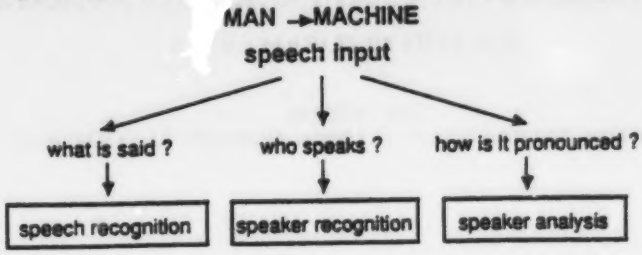

Fig. 2: Forms of speech input

* *what* is said? Here we ask for the content of the spoken phrase and we call it **speech recognition.**
* *who* speaks? This is the question for the speaker and we have **speaker recognition.**
* *how* is it pronounced? Here we ask for the momentaneous psychic situation of the speaker which can be defined as **speaker analysis.**

We will omit speaker analysis here since its application is restricted to very special medical fields.

2.3 Speech recognition

Speech recognition is a very new field of signal processing. There are many useful applications for it, not only in the robotic area but in many other - mainly technical - fields. Some arguments for speech recognition are listed below.

* *Speech is the most important form of human communication*	* *hands and eyes are free for other activities*
* *communication with machine and other humans is simultaneous possible*	* *system can be used by blind and other disabled people (e.g. motoric disabled)*
* *freedom of movement and orientation*	* *information input in dark and dusty rooms*
* *user is not bound at a fixed place*	* *compatible with radio and telephone (remote control by voice)*

Table 1: Arguments for speech recognition

Another advantage is the information input speed (fig. 3).

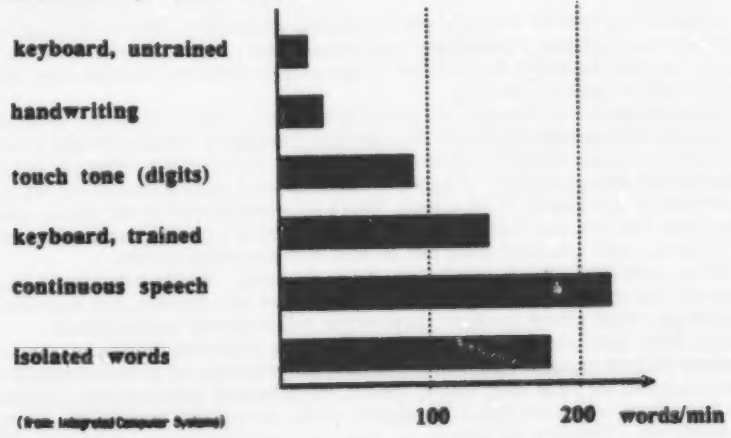

Fig. 3: Comparison of different forms of input

As shown, in the case of continuous speech input we are in the order of 220 words per minute. Using isolated word recognition we have about 180 words per minute. On the other hand a keyboard input yields about 30 to 40 words per minute. Thus speech is the fastest kind of information input.

The *recognition process* is based on comparisons between patterns which are stored in a memory and patterns which are pronounced in an actual situation.

Going a little bit more into details, we have to distinguish between two processing phases (fig. 4): the 'learning phase' or 'training phase' and the 'working phase' which is the actual application.

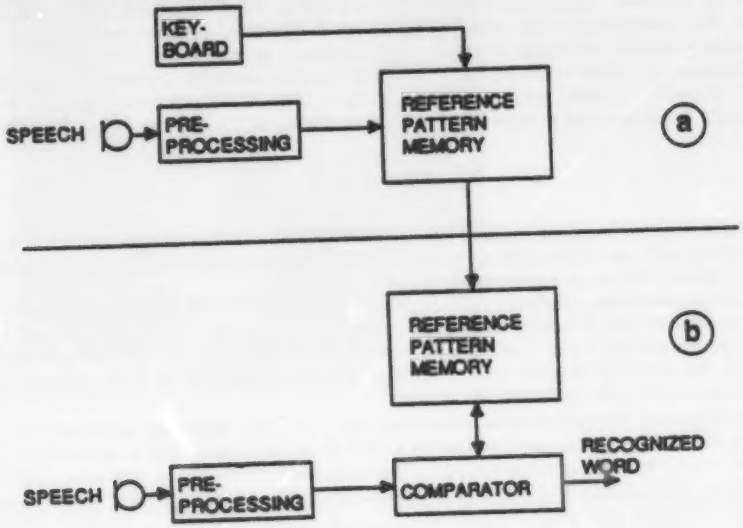

Fig. 4: Principle of speech recognition (isolated word recognition).
a) training phase, b) working phase

In the training phase each of the words of the related vocabulary is pronounced, processed and stored as reference pattern in a memory. Simultaneously the meaning of each word is fed in by a keyboard and distributed in a unique way to the related pattern. After all words have been trained, the system is ready for the working phase. If any word of the vocabulary is spoken, it is firstly processed in the same way as in the training phase and then made available in a comparator. Now all of the reference patterns of the training phase are compared succesively with the actual word pattern, the reference pattern with the maximum similarity is selected and its meaning is given out.

In most cases the speech spectrum is chosen for processing. Most of the existing recognizers use a set of filters (filter bank) for generating a coarse representation of the spectrum /6, 7/.

Although the basic idea of speech recognition is very simple, the recognition process bears many serious problems in detail. One of it is due to the fact that nobody is able to pronounce the same word twice with the same duration. For this reason, we have to take into consideration that equivalent words of the training and the working phase have a different length. The computation of the distance measure therefore requires a so-called 'time normalization'. This procedure is very complex and by no means a linear operation because fast and slow speaking influences sounds in a very different manner. As an example, vowels are much more affected than plosives. (As proof, compare the fast and slow pronounciation of the word 'tab', where the time difference mainly comes from the length of the 'a').

The time normalization problem was a crucial problem in the past and was solved in principle during the 70's by Itakura and Saito /6, 7/. Now the way was free for the development of powerful speech recognizers.

The *state of the art* for recognition systems can be characterized by a confusable number of devices which work more or less reliably. We want to restrict ourselves to two systems which are at the top of development. One system is 'Calltalk'. It has a 500 word vocabulary, recognizes words and short sentences and the price is in the order of10,000 $. Another very famous system is from Marconi ('Macrospeak'); its vocabulary size is 160 words which can be recognized in a connected modus.

A very important classification of recognition forms has to be mentioned, namely *ordinary speech recognition* and *speech understanding*. Recognition in its fundamental form means that all of the details of a spoken utterance have to be recognized, while speech understanding aims at the *meaning* or the *semantic content* of speech. As an example let us consider a voice controlled robot. Someone commands: 'turn to the right' Being equipped with ordinary speech recognition the system would state: (it was said) 'turn to the right' and it might display the command on a display. A speech understanding system, however, would understand the command and would execute it.This example makes clear that in most cases we need speech understanding, above all, if we control a system or a machine by voice.

At first sight one might believe that speech understanding is more difficult than recognition. This, however, is not always true. From a recognition system we expect that all details of a spoken phrase have to be recognized, while an understanding system only needs the recognition of the semantically relevant words. Continuing our example, in a command 'please turn to the right' the word 'please' is irrelevant for understanding (but not for recognition).

2.4 Speaker Recognition

Speaker recognition - more precisely *speaker verification* - is useful in all cases where systems or data banks have to be protected against unauthorized access or use. In a similar way verification systems can protect doors of computer centers etc. which are voice-controlled ('acoustic identity card').

Speaker recognition is based nearly on the same technique as speech recognition. Thus we have a training phase where a certain speaker has to pronounce words or a sentence which are demanded from the system. Simultaneously, the speaker has to identify himself, and his name (or code number) is distributed to his speech pattern.

The working phase, however, is different to speech recognition. At the beginning of the working phase a certain user - or the person, who pretends to be that user - repeats the utterance of the training phase and additionally types his identity code (name/code number) into the system. The system fetches the related pattern from the memory and compares it with the actual pattern. As the result of the comparison a similarity score is computed which leads to acceptance or rejection of the speaker.

One may ask how reliable the speaker recognition is, keeping in mind that there are very good professional imitators, who can deceive a human listener perfectly. Without going into details it can be stated that a top system is superior to the human. One reason is that the system can evaluate the speech signal more precisely and on the basis of more parameters than the human ear.

2.5 Dialogue systems

A real communication is *bi-directional*, i.e. in the communication act the partners change their role from the active part (speaking) to the passive one (listening) and vice versa. Obviously in a direct communication between humans speech is dominant, and self-evidently we do expect a spoken answer to a spoken question.

In a man-machine communication a dialogue form is necessary, too, since we need a confirmation of the system for correct recognition. Otherwise an uncontrolled or unexpected system reaction might occur.

There are recognizers on the market which confirm inputs by a graphic output on a display or other optical indications (lights etc.). This kind of response, to our opinion, requires some additional mental processing steps by the user, while an acoustic output is seized immediately and expected by him, as mentioned before.

In addition to the confirmation the information output has two other very important functions: Firstly it guides the user in the training and the working phase. Mostly this item is done by a kind of menue where a set of alternatives are offered. This is both, an essential help for the user and a necessary presupposition for the vocabulary restriction. It should be emphasized here that an optimum menue design has a crucial importance for the user acceptance. Secondly, the information output informs the user about system conditions including errors and help functions.

3. APPLICATION OF SPEECH PROCESSING IN ROBOTICS AND REHABILITATION

3.1 Voice-controlled operation microscope

A very illustrative example for the use of speech recognition is the voice-controlled operation microscope. This device is used in the main by a surgeon, who operates eyes, ears etc. During the operation the surgeon looks through the microscope and his hands use the operation cutlery. If he wants to change the visual area or to focus, to take a photo a.s.o., he has no hand free. In the past these functions were controlled by a set of foot switches. They were difficult to handle and caused troubles in the upper part of the body including the hands.

A better alternative obviously is the microscope control by voice. The vocabulary size is small (in the range of twenty commands) and thus a low cost recognizer can be used.

As an example, the GSP company realized such a recognizer and built it into a microscope of the company Wild (which is a subsidiary of Leitz). Fig. 5 shows the system. The microphone of the recognizer is placed near the ocular (see the small black box with the yellow dot). The recognizer itself can be found in the background. The system contains a speech output module as well, which repeats commands and controls the training phase.

Each spoken command is acknowledged in order to avoid faulty commands, whereby the error might have been produced by either the recognition system or the user. Additionally, one foot switch has been retained and as long as it is not pressed, the commands are not executed.

The acceptance of the system stands and falls with the reliability of the recognition, without any doubts. This requirement could be met by several system design specifications and above all by performing more than one training phase and averaging of the reference patterns.

A high reliability, however, is not sufficient for a good acceptance. We found out that the system user is not willing to invest much time or patience to understand instructions or to train the system. Thus everything was done to optimize the user procedure. Now each word which has to be trained is spoken before, the user is guided during the whole training procedure and it takes only some minutes to complete the process. If any word is not recognized with sufficient reliability, it can be retrained individually.

There are applications imaginable which are similar to the operation microscope. If one has to count or describe elements under a microscope or on a screen, the eyes are busy and the registration of results means an interrupt of the proper activity because the eyes are needed for writing the information on a paper or typing it with a keyboard. Obviously an acoustic registration without diverting the eyes from the matter of consideration is much more effective.

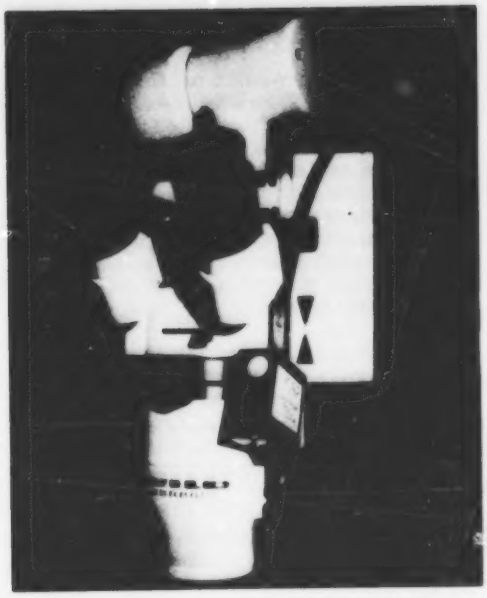

Fig. 5: Voice-controlled operation microscope (GSP Sprachtechnologie, Berlin)

3.2 Voice-controlled wheelchair

One of the first applications of speech recognition in the handicapped area was the voice-controlled wheelchair. The benefit for paralysed persons, especially quadriplegic disabled, is evident: they gain freedom of movement without the help of other persons. On the other hand, the user gets into dependence of a machine. As a matter of fact, the requirements to the reliability must be extremely high, otherwise the risk of an accident occurs. Fortunately the vocabulary which has to be recognized is very small ('forward', 'go back', 'right', 'left', 'stop' etc.). On the other hand it has to be considered that the environment in which the wheelchair operates might be very noisy (traffic noise etc.) which affects the recognition reliability remarkably - if no steps for noise cancellation were taken.

A well-proved voice control system for wheelchairs comes from the KEMPF company, the so-called KATALAVOX system, which is not restricted to wheelchairs but is also applied to operation microscopes, cars a.s.o. It has been in use since 1983. Fig. 6 shows the wheelchair.

Fig. 6: Voice-controlled wheelchair with the KATALAVOX system (KEMPF company)

3.3 Speech recognition for environment control

If we think of a paralyzed person, who is not able to open the flat door, to switch on/off the lights and to use the telephone, then it becomes clear that a voice control of these 'environment' functions is more than necessary. As a matter of fact, the control of environment functions is no task for a robot system in the strict sense. We don't need a robot hand to execute the commands, it can be replaced by a 'voice remote control'.

It seems to be useful to concentrate the location of voice control near to the most important communication device, which is - of course - the telephone.

There are special telephone sets, e.g. for visual impaired persons, with enlarged keys. Some of these keys do not serve as dialling keys but as control keys for environment control. In order to go a step forward to the handicapped and here to the paralyzed persons, keys might be replaced by a microphone and a speech recognizer, which executes these functions. Such a voice controlled telephone has been realized in our institute and is now under test.

4. PROBLEMS AND RESTRICTIONS FOR VOICE CONTROL

Although voice control has essential advantages compared to other techniques, there are, on the other hand, problems and restrictions (table 2).

a) speaker dependent isolated word recognition

* *time normalization*

* *amount of arithmetic operations (typ. 500,000 ops./s)*

* *dissimilarity of reference and test patterns*

* *recognition reliability dependent on phonological similarity/dissimilarity of words of the vocabulary*

b) same as a) but speaker independent

* *generation of representative reference patterns*

c) connected speech recognition

* *segmentation problem*

key problems for a) to c):

* ***ENVIRONMENT NOISE and***
* ***RESPONSE TIME***

Table 2: Problems of speech recognition (small selection)

We will focus our attention here on two main problems.

For many applications the *response time* (i.e. the time between the end of the spoken word and the complete recognition) must be shorter than half a second, otherwise the system cannot be controlled satisfactorily. If we take a wheelchair driver as example, it becomes clear that a delay of the command execution (e.g. a 'stop - command') might have serious consequences. In general, if we have a process which has to be controlled immediately and continuously, a voice control will be too inflexible and probably too unreliable compared to a pressed key or a hand-controlled regulator. As an example, we might consider a car driver who is blind and who gets control instructions from a co-driver. This situation illustrates the dilemma of control instruction and execution (which is, indeed, a dilemma, although the speech recognition works perfectly). It's not only the delay between recognition and execution, but a *quantitative* problem in addition. Thus a command 'turn to the right' will be executed in a strong or moderate manner, and both kinds might be wrong.

A crucial problem is *noise*. Experiments have shown that recognizers fail if they are used in a really noisy environment. Naturally companies which sell recognizers, only publish recognition results which have been measured in a very clean (and unrealistic) laboratory environment. Thus one can find recognition results in the order of 98% (i.e. 2% errors). Using the same systems in a normal office environment might reduce the rate to 70%, which is of course not acceptable. We believe that most efforts have to be done to improve the 'robustness' of recognizers (against noise) and not to extend the vocabulary size or to use more complex forms of speech recognition.

5. FINAL COMMENTS

Up to now we have discussed technical aspects of voice control. We shouldn't end our paper without some words of more general items which are, nevertheless, of great importance.

First of all we have to state that there is a lack of knowledge in the speech processing area regarding *human factors*. This aspect could fill a whole conference without any doubt.

Another aspect is *system integration*. It means that a synthesizer or a recognizer is only a part of a system. As an example, a typical recognizer module which costs some hundred $ needs a host computer for some thousands of $. Additionally, we must have a special software a.s.o., a.s.o., which at least increases the total price to more than ten thousands of $.

Then the *menue/dialogue technique* must be considered. It has a close link to the first item (human factors). How can we design a dialogue which is adapted to special kinds of disability? What is the optimum system reaction to a spoken input? In many cases the most natural response is speech. However, it might be more useful to combine the speech output with other forms like graphic displays or a Braille line /2/.

A last point, *commercial attractivity*, has a very pessimistic touch. We all know that the development of systems for the handicapped makes no profit. That's why the industry (nearly) has no interest to develop such systems.

In my mind there are two ways to diminish the dilemma.

Firstly, the devices have to be designed in such a way that they are an attractive solution for the non-disabled as well. The adaptation to the special kind of disability should be performed as additional facility.

Secondly, we need more financial support from governmental institutions which enable universities or non-profit companies to do research and to develop new devices. The same is valid for manufacturers or companies which may get support from governmental funds.

Probably the most crucial point is the individual readiness to *accept a handicapped person* as a collaborator, even if he has a reduced efficiency and/or he needs more help than a non-disabled colleague.

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AN EXPERT VISION SYSTEM FOR LARYNGOSCOPIC DIAGNOSIS

C.R. ALLEN, H.C. YUNG, A.E. ADAMS
The University, Newcastle upon Tyne
NE1 7RU
England

R BERESFORD, A WELCH
Department of Ear, Nose & Throat
Freeman Hospital
Newcastle upon Tyne England

1. INTRODUCTION

Intrusive methods of observing the movement of the laryngeal muscles using an endoscope [1] are finding more and more application in medical examination and diagnosis [2,3]. In this paper an automated vision analysis has been applied to selected static images derived from a video recording of an endoscopic examination of the vocal folds of patients. The machine vision analysis has been implemented using a strategy of iconic 2D measurements of the shape of the larynx. The measurements are derived from a connectivity analysis of segmented outlines from the grey level image, which are used to produce rotationally and size invariant measurements. The on-line results which are made by a PC-based image analyser, and then compared with a trained set of similar measurements stored in the computer database, using a statistical classifier package to provide confidence of diagnosis. The system which is a research prototype has potential for use as an on-line systems adviser using a database of laryngoscopic illnesses, encoded as 2D shape measurements. This may be of considerable value in general hospital practice complementing endoscopic examination. The paper describes the types of images which are recordable using commercially available endoscopes, and how the analysis is undertaken automatically by the microcomputer, with benchmarks of response of diagnosis. Section 2 discusses laryngoscopic methods, section 3 the experimental ENT endoscope system and section 4 the measurements adopted using image analysis. Section 5 discusses the role of statistical measurements, and use of the database of previous patient measurements of the larynx.

2. LARYNGOSCOPIC EXAMINATION AND DIAGNOSIS

Phonation is the regulation of the pulmonic egressive air-stream initiated during speech, by movements of the vocal folds. The adduction and consequent vibration of the folds produces the phonatory state called voicing: whilst abduction and the consequent absence of vibration is the state of voicelessness. During speech the folds are constantly alternating between these states. Figure 1 shows two typical captured images taken using an endoscope placed via the mouth close to the back of the throat, illuminated via the optical fibre bundle and the image focussed in the normal way using a geometrical lens via an eyepiece. The left image shows the shape of the glottis when completely open, and the right image the converse point. The examining doctor has the facility of finely adjusting the attitude of the small optical bundle end, using a simple lever at the eyepiece.

There are a variety of clinical techniques devised to monitor phonation: acoustically, aerodynamically, glottographically and visually using endoscopy. The first method is the least intrusive to the patient but omits direct information about vocal-fold movement and can fail to distinquish mechanically different phonations. Glottographic examination can indirectly observe the cycle of vocal fold movements by electrical transduction shown on a display monitor, but has the disadvantage of showing only the trans-sectional area of the glottis (the space between the folds) not the folds themselves. Aerodynamical methods can measure the mechanical efficiency of the folds and quantify the regulation of the air stream, but does not offer direct information as to the physical state of the folds. This is however possible using

endoscopic examination, the most intrusive method.

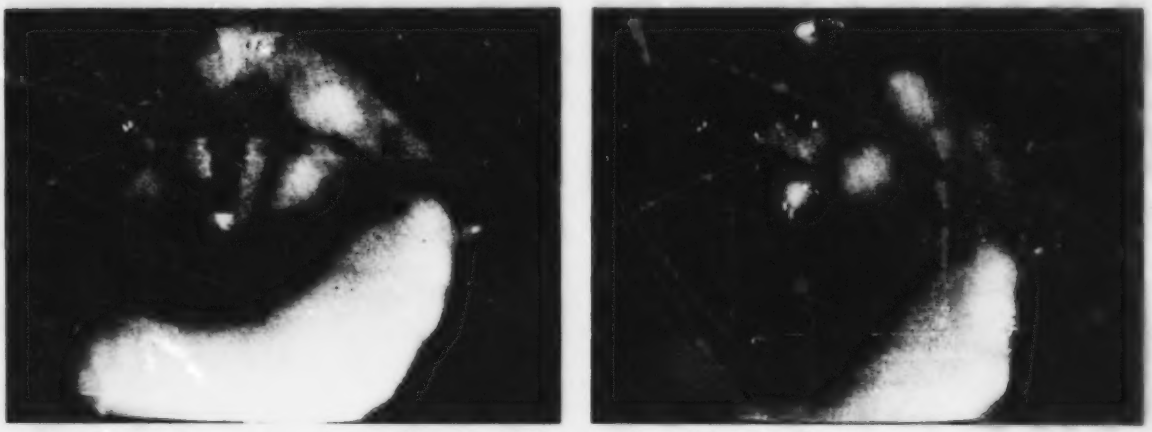

Figure 1. Grey level images captured on a magnetic recorder using a small CCD camera mounted alongside the endoscope eyepiece.

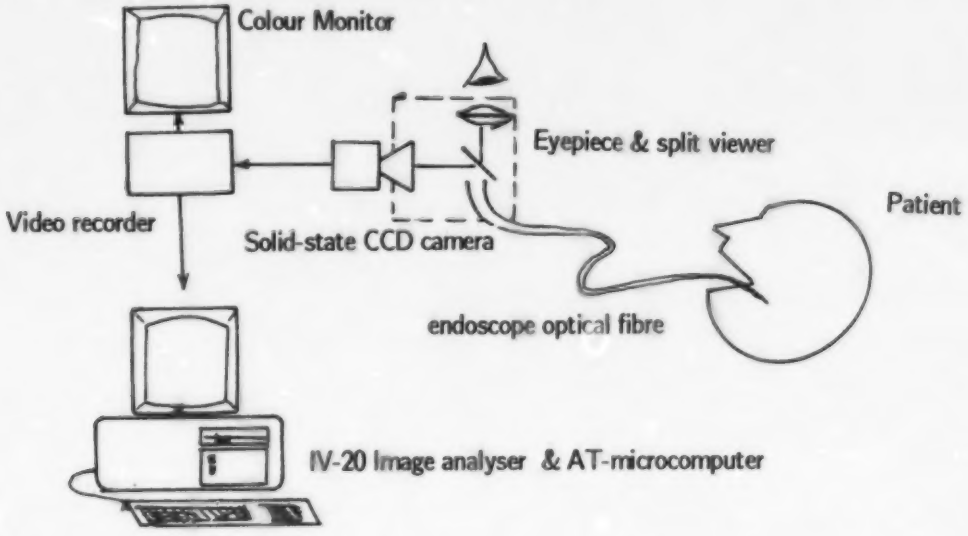

Figure 2. Schematic of the On-line diagnostic image analysis system, with B&K endoscope.

3. INTEGRATION OF COMPUTER ANALYSIS INTO ENDSCOPIC EXAMINATION

Figure 2 shows the experimental system used in this study. The doctor examining the patient may observe the larynx via the endoscope eyepiece, whilst a quarter mirror splits the image so the view is cast upon a compact CCD video camera, attached at the second viewing point. The CCD camera has a macro lens, and zoom facility so fine

tuning of the focus is possible on-line. The image is displayed as a composite video colour image on a CCIR 50 Hz monitor, which is available to the systems programmer and / or other medical personnel who may observe the images.

Simultaneously, this video signal is quantised into a 256x256 grey level image and stored in a microcomputer frame store using a 6-bit quantisation. Any desired static image may be permanently captured using a simple key touch on the image analyser. The image analyser used in this project was an IV20 micro analyser, based on the IBM-AT computer series and supplied by Joyce Loebl Ltd [4]. The endoscope in use at the Freeman Hospital Department of Ear,Nose and Throat is a Bruel & Kjaer endoscope [5].

An unedited clinical recording of an hour's examination is stored on video, and if the systems programmer is available, selected images may be digitised and permanently stored on the computer in a wide variety of forms, including a complete frame record stored onto disk, or more usefully as a set of shape measurements, made on-line, and then stored as a compact record into a database using the 20 Mbyte hard disk storage available on the microcomputer-AT.

4. IMAGE ANALYSIS AND SHAPE MEASUREMENTS OF THE GLOTTIS

Much clinically useful information may be gained by using a flexible nasopharyngeal endoscope. The sequence of vocal fold movements can be observed using a strobed light source. Alternatively a video recording can be made by splitting the viewing position between the viewer's eyepiece and a CCD colour/ grey level camera, which is the visual transducer used as input to a standard video recorder.

One major advantage of a permanent record on video tape is that specific conditions of the vocal folds can be stored, retrieved and studied in a collaborative way. It is also an ideal resource for off-line computer analysis.

The observation of such images can be made even more effective if such image records may be enhanced by enlargement, clarification of boundary edges of the vocal folds and the glottis. In addition besides image enhancement or clarification through edge extraction, images are susceptible to techniques of image analysis [6], which includes the use of patttern recognition methods to classify measurements with a trained set [7].

Image Processing Shell File

It has been found that the larnygeal image monitored by the CCD camera exhibits several special features, characteristic of the nature of the environment. The larynx is illuminated by white light, and the image contrast and colour is very good. Although the level of lighting is controlled, the back of the throat has saliva and muscle colour which often produce contrast highlights within the image e.g. peak whiteness. In addition the position of the glottis, the area of interest between the larynx folds will move about in the image frame, as the examining practitioner adjusts the endoscope end effector, controller by the lever mechanism.

If on-line and automatic image capture and analysis is to be available, then all these variables have to be known and controlled within a computing shell file, which is automatic but flexible enough to allow tuning during a set of image measurements.

The IV-20 image analyser card is supported by a suitable programming environment, which offers similar processing facilities to an in-house image analysis package called VIPS [8]. The commercial package used in the study reported here is GENIAS-20, provided by the Joyce Loebl Ltd, England as part of their support of the IV-20 analyser [4].

The Analysis Sequence

Figure 3 shows an extract of the image analysis sequence developed by the study and found to provide a suitable method of analysis of the larynx colour images.

```
MAIN MENU
Multiply                    {within window}
0                           { x result : low }
3969                        { x result : high }
GREY ARITHMETIC
Transform
TRANSFORM TABLE
Define
TABLE SETTING
Quit
Grey
0                           { transform output : low }
63                          { transform output : high }
TRANSFORM TABLE
Quit
..
GREY OPS
Linear
LINEAR FILTERS
Mean
NON-LINEAR FILTERS
Sharpen
-
-
```

```
Measure
Objects
0                           { Nesting levels? 0= none }
Yes
MEASUREMENTS 1
Select-all
MEASUREMENTS 1
Quit
MAIN MENU
Binary
BINARY OPS
Image-based
Thin
Yes
IMAGE-BASED OPS
Border
 2                          { width?[1..] }
IMAGE BASED OPS
 -
```

Figure 3. Extract from the Image Processing Shell.

The shell defines a window of N x N pixels size, where all the analysis takes part. This is a particularly valuable feature, as image pre-processing functions like region smoothing and edge crispening depend on linear 2-dimensional filtering convolutions, which are computationally very intensive, and very slow to execute in software on a standard von-Neumann machine like the AT microcomputer. The IV-20 also helps by providing dedicated hardware modules which execute at real-time video rates.

Binary Analysis

The initial steps of the analysis use a number of pre-processing operations within the defined window in order to make the glottal region more distinct than its surrounding laryngeal folds. These operations included convolution using edge crispening, non-linear operations like median filtering to smooth the region, and grey level operations like multiply.

Histogram equalisation is also useful to define a grey level threshold at a level suitable for image binarisation. The defined window and grey level histogram of pixels within that window are shown in Figure 4a. Figure 4b shows the segmentation of the glottal regions from the surrounding folds, based on a binary threshold determined from Figure 4a. It was also found valuable to perform a binary erosion and then dilation of the image over the region, to remove spurious noise points. This operation does not affect the shape of the glottis.

The separate regions are then analysed using boundary edge following methods [4,5,6] which are based on the classical Freeman chain coding algorithm. Figures 4c and 4d show the definition achievable of the glottis as a region measurement, and latterly as a collapsed arc formed by binary skelotonising. The vectors which define each defined region provide a method to accurately measure the shape of the region. The measurements are shown for Figures 4c and 4d in the next two Figures 4e and 4f respectively.

Measurements File

Figure 4e and 4f summarise the useful information gained from the analysis, and so are stored as a results file on hard-disk. The datafile contains an accurate set of iconic measurements related to the shape of the glottal region.

Fig 4a Image window

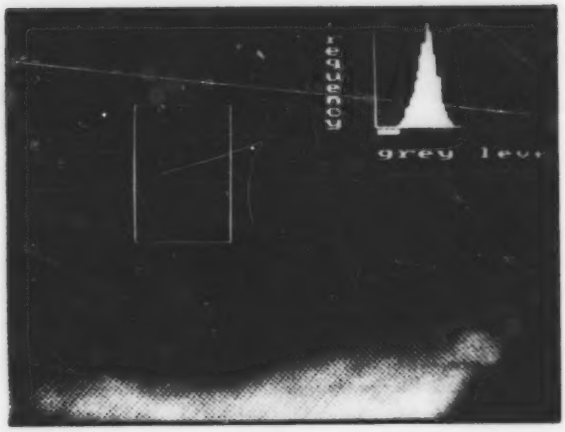

Fig 4b. Pixel Intensity Histogram

Fig 4c. Boundary regions of the glottis

Fig 4d. Skeleton arc measurements

Fig 4e. Measurements file for region 1

Fig 4f. Measurments for arc 1

5. DISCUSSION

The measurements described in section 4 provide a quantitative set of parameters which characterise the shape of the glottal region. Other record data is also required to be linked with the visual results including patient details, voice exercise used, and phase shift in the laryngeal wave cycle. Each computed results file is very compact, being only a few hundred bytes of data, compared to the many hundreds of image frames, which define the movement of the larynx.

The problems associated with tracking the movement of the glottis, and its position within the small image window are broadly solved. The movement of the glottis can be followed frame by frame, automatically using the positional information shown in Figure 4e,f. The centre of gravity can be then used to reposition the centre of the window, at each analysis automatically. In addition histogram equalisation prior to binary object segmentation has proved useful in defining an accurate threshold level.

The measurements made in Fig 4e,f are all rotationally invariant parameters associated with the two regions of the glottis. By combining ratios of these parameters, size invariant (dimensionless) quantities are obtained e.g. AREA ONE / (PERIMETER ONE * PERIMETER ONE). A set of these invariant parameters may then be used to characterise the shape of the glottis and laryngeal folds.

Statistically Derived Classification

The use of statistical classifiers for the classification of the glottal shape is currently under investigation. This technique has previously been developed in the robotic vision field [9,10] to help to quantify the certainty of classification of component workpieces. On-line the shape measurements are compared using Bayesian statistics with a trained set of measures, and thus a figure of merit is associated with the classification.

In the current medical application the trained set will be derived from model patient visual records, which have been expertly diagnosed by specialists. Then routine endoscopic examination may use the microcomputer system to give a match from its database as to the probable diagnosis. The next step in the system development will be the classifier shell, which will complete the computer based expert system.

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ROBOT VISION TECHNIQUES IN THE ASSESSMENT AND TREATMENT OF DIABETIC RETINOPATHY

D T Pham
Robotics Research Group
Department of Mechanical Engineering
University of Birmingham
Birmingham B15 2TT
United Kingdom

Telephone 021 - 414 4146 (Direct)
Telex 338 938 SPAPHY G

Abstract

This paper reports work by the author's team towards applying robot vision techniques in the assessment and treatment of diabetic retinopathy, an anomalous condition of the retina caused by diabetes. Most of the effort of the team has been spent on devising software for rapid and accurate assessment of the nature and extent of retinal lesions. The techniques investigated include retinal image enhancement by relaxation, automatic segmentation by thresholding and edge detection, feature recognition using "Artificial Intelligence". Following a review of research by previous workers, the methods adopted in the current project, the results obtained, and plans for future investigations will be described. The main results discussed in the paper are: an ultra-low distribution image compression algorithm for reducing the large amount of grey scale data to be stored in mass diagnosis of diabetic retinopathy, an extremely sensitive filter for detecting linear features in retinal images, and an intelligent rule-based system for recognising retinal blood vessels from all the linear features found by the filter.

Background

Diabetic retinopathy, a disease of the retina resulting from diabetes, is a very common cause of blindness in adults under 65 years of age [1]. If diagnosed in time, the disease can be treated and blindness averted by using laser photocoagulation, a technique involving firing laser pulses onto the affected areas of the retina. This operation is very time consuming, taking a skilled surgeon from 30 minutes to 2 hours per eye. The total time involved can be considerably longer because of the pre- and post- surgical analyses needed to assess the nature and extent of the retinal lesions and the effectiveness of the treatment. Unfortunately, existing health care facilities and manpower are inadequate compared to the large number of diabetic retinopathy sufferers - it has been estimated that there could be up to 100,000 people with that condition in England and Wales alone [2].

In this paper, research by the author's team into the use of robot vision techniques in diabetic retinopathy assessment and treatment will be discussed. The aim of such research is to produce systems to enable the ophthalmic surgeon to carry out his tasks speedily and accurately while reducing the strains on him, so that he can deal with many more patients than at present. The paper begins with a review of related previous work. The methods adopted in the current project, the results achieved, and plans for future investigations will then be described.

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Research on Speech I/O at the National Aeronautical Establishment

Melvyn J. Hunt, Claude Lefèbvre & Carl P. Swail

National Research Council
National Aeronautical Establishment
Building U61, Montreal Road
Ottawa, K1A 0R6

Summary

This paper describes the work of the NAE Speech Research Centre and discusses its relevance to the theme of this Workshop. Section 2 argues that speech is often — though not always — the most natural means of communicating with robots. Its most solid advantages lie in its not requiring the use of hands or eyes. Speech input should be complemented by speech output, and the speech generated should use the full range of information-bearing cues available in spoken language. The next section summarises the work of the Centre, which is directed towards aeronautical applications, and points out the similarity between the needs of these applications and of those being considered at the Workshop. The remaining sections discuss research activity at the Centre in the following areas: development of software for display and processing of speech and other signals, the development of robust speech recognition using an auditory model, speech recognition performance evaluation, work with a sophisticated commercial speech recogniser, and development of highly intelligible speech output using pitch-synchronous LPC.

1. Introduction

The Speech Research Centre of the National Aeronautical Establishment's Flight Research Laboratory carries out research in a range of areas affecting speech technology. It is located on the National Research Council's Uplands campus close to Ottawa International Airport.

The purposes of this paper are first to argue the relevance of speech input and output technology to the theme of this workshop, namely Robotic Applications in Medical and Health Care, and second to give an overview of activities at the Centre that are pertinent to the theme.

2. The Relevance of Speech Technology

Speech input — that is, speech recognition — offers two general classes of advantage over alternative methods of communicating with robots. First, it is often faster, more natural and more flexible than the alternatives. It is, after all, the form of communication we use most often between ourselves. In principle, it does not require any special training — a feature that is particularly attractive for older users, who might be confused and intimidated by less natural forms of communication. While keyboard input can be made as fast as speech by having single-keystroke commands, this option limits the number of commands possible and makes it difficult to change the command set. By contrast, the set of speech commands to be used can be easily changed.

This class of advantages for speech input should not be exaggerated, however. Current speech technology requires users to speak in a more disciplined and consistent manner than they need do when talking to another person. Moreover, current systems can accept only a limited range of words and grammatical structures and can make only limited inferences from the input they receive. The very naturalness of speech input makes it all too easy to project human capacities for speech understanding and reasoning onto the machine.

Moreover, not all communication with machines is most naturally carried out by voice. Speech is well suited to discrete and often high-level commands, such as an instruction to a robot to turn on the radio; it is not well suited to continuous low-level guidance, such as might be needed to guide an unsophisticated robot across a room. The Fraunhofer Gesellschaft in Karlsruhe had an instructive demonstration in which the task was to have a robot insert a peg in a hole. Using spoken commands such as "up," "down," "stop" *etc.* the task was virtually impossible, while by using a simple joy stick it was trivial. The extent to which speech control offers naturalness and convenience clearly depends not only on the sophistication of the speech technology that can be used but also on the sophistication of the robot itself in being able to accept high-level commands.

For the present, a more solid set of advantages for the use of speech input technology rests on its not requiring the use of hands or eyes. Robots can thus be controlled from across a room, or by people who do not have use of

their hands or eyes. Equally, speech input can be used by people whose hands are fully occupied with other tasks. One of the major speech recognition demonstrators being developed under the U.K. *Alvey* program, for example, is aimed at providing voice control for a microsurgeon, whose hands and eyes are already fully occupied.

Much of the hands-free/eyes-free advantage of speech control is lost if it is not complemented by feedback in the form of speech output from the robot. It is true that some spoken instructions provide their own implicit feedback in as much as the robot can be seen to carry out the action required. Clearly, however, speech output is essential for blind operators; and even for sighted operators whose eyes are not otherwise occupied, spoken confirmation by the robot of what it has understood can help the operator prevent it from taking erroneous and possibly dangerous actions. Speech output is also desirable when a dialogue with the robot is necessary, or when the robot must issue a warning or announce a problem.

Our cultural emphasis on written language [1] often leads us to feel that the content of a spoken message is specified completely by the sequence of words used. This is emphatically not the case. In spoken language we use intonation and timing to help our listener understand the structure of the sentence and which words are important in it. These features together with voice quality also allow us to communicate — or sometimes cause us to betray unconsciously — how we feel about what we are saying. The use of the word "emphatically" a few sentences ago was necessary precisely because we cannot invest written words with the emphasis that we routinely use in speech.

The common perception of the voice of a robot is of a voice speaking with a fixed rhythm and a flat intonation. But if speech output from robots is to be effective, it should be maximally intelligible and should contain all the cues to understanding that we ourselves provide. The style of the speech should also be appropriate to the message: greetings should sound friendly, and urgent messages should sound urgent. At the same time, we must be aware of the danger of making robots sound too human, if the tendency mentioned earlier to project human powers of inference onto a speech-controlled robot is not to be reinforced.

The technology to allow useful spoken interaction with robots is available now. Since we ourselves communicate so effortlessly by voice, however, it is easy to underestimate the difficulty of automating the skill and to believe the exaggerated claims of some inventors and manufacturers. Current technology imposes restrictions on, for example, vocabulary size, speaking style and signal quality that limit the convenience of voice control. Moreover, some of the applications covered by the theme of the Workshop are in areas where cost constraints are severe, and the best technology is not usually the cheapest. Advances in the next few years in hardware and in algorithms should alleviate both these problems.

3. The NAE Speech Research Centre

The location of the Centre in the National Aeronautical Establishment makes it natural that its work should be aimed primarily at aeronautical applications. Since the hands and eyes of pilots, particularly helicopter and fighter pilots, are heavily loaded, there is a pressing need to provide them with an additional channel of communication with their aircraft. Speech warning messages are now common. Speech input has been successfully tested in helicopters and fighters, notably in France and the U.K., and the next fighter to enter service in the French Air Force, the *Rafale*, will have several secondary functions controlled by voice. A synthesiser will provide spoken feedback.

In addition to these applications in the cockpit, there is growing interest in speech I/O for air traffic control, primarily for simulation and training. At present, air traffic controllers working with a simulator give spoken instructions to a *pseudopilot*, who provides spoken feedback to the controller and simultaneously keys in the instructions for the simulated aircraft. The introduction of speech recognition and synthesis would remove the need for the pseudopilot.

The characteristics of these applications are remarkably close to those of many applications with robots. On the recognition side, the need in both aeronautical and robotics applications is for reliable performance with a limited vocabulary and simple sentence structures and usually with a single user. Cockpit-based applications must cope with high levels of interfering noise and with changes in the voice caused by variations in the noise level at the pilot's ears, by vibration, high g, and workload stress. By contrast, applications to automatic dictation machines, for example, are characterised by large vocabularies and complex sentence structures, but the conditions in which the user works are generally free of noise and physical and mental stress. Apart, perhaps, for workload stress in surgical applications, the conditions in which robots of the kind being considered here are likely to be used are also largely free of the extreme noise and stress problems encountered in aircraft. However, many users of robots in domestic or rehabilitation situations might be expected to have speech control difficulties that would produce similar effects to those of the stresses on pilots. Moreover, if robots are to be controlled remotely by voice without the use of a head-mounted noise-canceling microphone, the varying separation between the user and the microphone will cause changes in loudness and spectrum balance similar to those encountered with pilots. Background noises will also be picked up along with the speech.

Turning to speech output, there is no need in the aeronautical applications being considered for an unlimited vocabulary, as would be the case for talking books, for example. On the other hand, we believe it essential that pilots should be presented with speech that is as natural and intelligible as possible. Tests have found [2] that when listeners are presented with speech from apparently intelligible text-to-speech synthesis systems their reaction times are slower and their comprehension of the message is poorer than is the case with natural speech. It therefore seems unreasonable to give pilots the extra processing load that text-to-speech systems would impose. Systems in which natural speech is encoded in terms of a compact set of parameters, whose values can be adjusted to change prosody and voice quality, seem to be ideal for the cockpit. Synthesis work at the Centre is therefore aimed in this direction. Such systems are also well suited to applications with robots.

The following sections describe briefly the activity of the Centre in some areas that relate to the theme of the Workshop.

4. Software Development

We believe that an effective set of software tools for processing, displaying and listening to speech and other signals is essential for efficient research in our area. We work with the UNIX* operating system, and we have adopted the philosophy behind the UNIX software tools [3]. The standard tools are, however, heavily oriented towards text processing and ASCII files. We have developed a set of similar tools [4] for numerical processing with binary files: record manipulation, arithmetic operations, digital filtering, matrix algebra, *etc.* The programs take parameters via argument lists, and input and output is through channels that allow redirection and piping. Thus, the simple, modular programs can be linked together using the UNIX shell to construct units performing more complex operations. Each program checks its argument list and its input data carefully, and outputs informative messages in case of problems. It is virtually impossible to cause a program to crash. The inventory of tools is now comprehensive enough that it is rare that a new program needs to be written, even when a new research topic is begun.

Linked to the tools is a signal display package [5], which allows waveforms and spectrograms to be plotted and signals to be played out through a D/A converter. The program makes no assumptions about the kinds of signals it is dealing with. Its power comes from the ability to call up any of the software tools from the display program and apply them to portions of signal designated within the program. Thus, there is no facility in the display program for generating, for instance, a log power spectrum. Rather, the portion of signal for which the power spectrum is to be computed is designated in the program, a sequence of tools for computing a log power spectrum is applied, and the result is displayed as just another signal. This structure allows the program to cope with the unforeseen needs of new users.

A few more features of the display program may be worth mentioning. It remembers the last twenty commands typed, and can be made to repeat specified commands. For each user, the program stores the state it was in was in at the end of the last session, and this state can be optionally recreated at the start of the next session. A user can also jump out of the program temporarily (to check for the existence of certain files, for example) and then jump back in. The program can also be run from a mixture of ASCII command files and keyboard input, allowing demonstrations to be automated and providing a limited facility for defining macros. Typing and learning time is minimised by having the program make sensible default assumptions, and by having largely single-character mnemonic commands with an almost completely free syntax.

5. Speech Recognition Research — the Auditory Model

The central process of speech recognition is the comparison of the acoustic representations of speech sounds. Ideally, the comparison should give a reliable measure of the phonetic similarity of the pair of sounds being compared. While in large vocabulary systems factors such as language modeling can be important, for reliable recognition of small vocabularies with high acoustic variability, the representation and comparison of the acoustic signal is crucial. It should be sensitive to features that relate to the phonetic identities of speech sounds while being insensitive to other features that are affected by voice changes and signal degradations. Among the latter are indications of absolute loudness, of gross spectrum balance, and of details of low-level parts of the spectrum that would be sensitive to background noise.

Since speech evolved to be understood through human ears, it is not surprising that our ears are generally better at recognising speech than current speech recognisers are. This is so even with nonsense words, where we cannot use our knowledge of the language, and it is particularly so with speech containing acoustic variations and degradations. It is natural, therefore, to try to emulate the acoustic representation provided by the ear: that is, to develop an auditory model for automatic speech recognition.

*UNIX is a trademark of AT&T Bell Laboratories.

There are currently many alternative computational auditory models. A recent issue of the *Journal of Phonetics* [6] gave accounts of many of them. The approach taken at the Centre [7] is different from most of the others, however, in that we are aiming to reproduce *psychoacoustic properties* rather than physiological mechanisms. Our model is sensitive to the frequencies of the lower formants (acoustic resonances in the vocal tract), which are known to contain most of the cues to the identities of speech sounds [8,9]. It shows simultaneous masking [10], which suppresses irrelevant acoustic information in the speech signal as well as low-level background noise. Finally the output of the model is almost completely independent of the level of the input signal and substantially independent of changes in overall spectral balance. These properties give the model good resistance to the effects of shouting and of voice changes caused, for example, by noise in the ears of the speaker [11], and to changes in room acoustics.

Our auditory model is also unusual in having been shown to provide a clear advantage over a conventional (mel-scale filter bank) representation in speaker-dependent and speaker-independent recognition tests with both male and female speakers [12]. With signals degraded by added noise or linear filtering the advantage of the auditory model is large. Because of these encouraging results, the further development of the auditory model and its realization in real-time hardware is currently the highest priority activity at the Centre.

6. Evaluation of the Performance of Speech Recognizers

Knowing how well a recogniser will perform, both in an absolute sense and relative to its competitors, is clearly most desirable. However, the specification of the performance of a speech recogniser is not straightforward. Statements in isolation that a recogniser achieves "98% correct recognition" are meaningless: performance depends on the vocabulary, the conditions, and the speakers, and can vary wildly even when all these factors are controlled.

An aspect of the thorny problem of evaluation on which the Centre has concentrated is the interpretation of the output of connected-word recognisers. Such a device accepts continuously spoken sequences of words and outputs the sequence that it has recognised. The output may contain substitution, deletion and insertion errors, and its interpretation in terms of the input sequence is generally ambiguous, since many different combinations of insertions, deletions and substitutions can result in the same output sequence being generated from the input. A common method of interpreting the output, being employed in the current DARPA speech recognition program [13], actually finds the most *favorable* interpretation of the behavior of the recogniser, and thus inevitably gives biased performance estimates. By running a series of random-number simulations, we have been able to estimate the extent of the bias as a function of vocabulary size, sequence length and true performance [14]. The most salient result has been that estimates of the proportion of words correctly recognised can be estimated much more reliably than the proportion of total errors. This apparently paradoxical result comes about because the number of words correctly recognised is equal to the number of input words minus the number of substitutions and deletions. Unlike the total number of errors, this measure therefore effectively ignores insertions, and this makes it independent of the partitioning of errors into the three classes. Current DARPA scoring procedures report total errors, but as a result of this work a change to reporting proportion correct is being considered [15]. In addition, we have described [16] an alternative, more complex, scoring procedure that does give precise, unbiased results.

7. Work with a Commercial Speech Recognizer

To gain experience with commercially available hardware, the Centre bought a sophisticated connected-word recogniser with programmable syntax and a capacity to counter the effects of slowly varying background noise. The Neil Squire Foundation, an organization involved in developing computer-based aids for the handicapped, placed an NRC IRAP-funded co-op student, Ken Evans, with the Centre for three months. With his help, and that of an NRC contract employee, John MacKay, we were able to test the recogniser, understand its operation, and develop a demonstration application with it [17].

The tests showed that the capacity of the device to resist the effects of low-level added noise was excellent. On the other hand, the device was sensitive to secondary effects of noise, namely changes in the loudness and spectrum balance of the speech.

The most striking results concerned the training procedure. Although the device is designed to recognise words spoken in continuous sequences, the manufacturer's intended training procedure consists of having the speaker who is to use the device utter a single example in isolation of each word in the vocabulary. By exchanging training material between the recogniser and a host computer, we were able to compare this training method with an alternative in which typically fifteen examples of each word extracted from continuously spoken sequences are time aligned and averaged together. This alternative training method reduced the error rate by a factor of seven, and it resulted in speaker-independent performance obtained that was equal to the speaker-dependent performance using the manufacturer's recommended training method.

By training the device and carrying out recognition tests with a set of non-speech signals consisting of tones and chirps of varying lengths, frequencies and intensities, we were able to determine the characteristics of the acoustic analysis and the recognition algorithm used. These findings have since been confirmed with the manufacturer. Using simulations of parts of the recognizer, we were able to show that performance with women's voices could be considerably improved by a simple change to the acoustic analysis.

The demonstration application was the replacement of the keyboard by speech as the input to the signal display program described in Section 4. The demonstration worked successfully. It would allow a handicapped person unable to use a keyboard to operate the display program. However, it is unlikely that a person without such a handicap would choose to abandon the keyboard. The very features of the program that make it convenient to use with a keyboard — the single-keystroke commands and the free syntax — make it inconvenient for speech input. This experience is an illustration of the need to design an interface around the special characteristics of speech input and not assume that speech can be used efficiently as a direct plug-in replacement for a keyboard.

In passing, it is worth mentioning that all the tests, signal generation, and speech processing were carried out using the general-purpose software tools described in Section 4 without a single program needing to be written or modified.

8. Speech Output Work

The need for highly intelligible speech output with a restricted range of vocabulary and sentence structure can, we feel, best be met by manipulating the parameters of analysed natural speech. Linear Predictive Coding or LPC [18] is a well established technique for encoding natural speech in a compact form. Most applications of LPC, however, are to real-time digital speech communication systems, and this constrains the quality of the analysis. When speech is being analysed for later use by a speech output system, these constraints do not apply. Recordings can be made in carefully controlled conditions, and the analysis can be more sophisticated.

In parallel with a group at the University of Florida [19], we have developed the technique of pitch synchronous LPC [20]. The analysis is carried out between consecutive closures of the vocal cords, as the theory of LPC would predict to be desirable. The instants of closure are determined by a device called a *laryngograph*, which measures the varying r.f. impedance across the larynx as the vocal cords open and close, and was originally developed to help deaf people improve their control over the intonation and voice quality of their speech. The resulting synchronization between the analysis and the acoustic excitation of the vocal tract, together with the use of more complex analysis leads to a reliable parametric representation of the state of the vocal tract. This representation can be expressed in terms of the frequencies and bandwidths of the formants. The laryngograph also provides an essentially error-free indication of voicing and fundamental frequency (often called "pitch"). Errors in these areas are a common source of degradations in conventional LPC.

As recordings to be played at the Workshop will show, speech resynthesised from an analysis of this kind is highly intelligible and natural. Moreover, the parametric representation can easily be modified to change the duration, loadness and timing of synthesized words to adapt them to different contexts within a sentence and to change emphasis. The acoustic excitation and the formant parameters can also be modified to change the quality of the voice — to a whispered, rough or breathy voice, for example — and to change the apparent size, dialect and even sex of the speaker. Some progress has been made in giving emotional qualities to the voice, so that, for example, urgent warnings sound urgent, and in devising voices that are clearly not human without any loss in intelligibility.

The development of the pitch-synchronous system is being continued by Raymond Carr, a graduate student from the University of Ottawa. The Centre is also collaborating with the Centre for Speech Technology Research (CSTR) in Victoria B.C. on the development of a speech output system for teaching English to students in Japan. As part of this collaboration, the Centre will be supplied with real-time speech output hardware programmed for use in an NAE Flight Research Laboratory helicopter.

9. Concluding Remarks

We have tried to make the case for the inclusion of speech input and output technology in robots for medical and health care applications, and to point out the similarity of the needs of these applications and those of our primary interest, namely aeronautical applications. The paper should give Workshop participants some feeling for the range of our activities. More detailed accounts can be found in some of the publications listed and in a recent NAE report [21].

Acknowledgments

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ROBOTIC PREANALYTIC PROCESSING OF HAZARDOUS BLOOD SPECIMENS FOR CLINICAL LABORATORIES

W. GOODLPHIN and J.A. McEWEN,
Andronic Devices Ltd.,
Vancouver General Hospital Research Institute,
Box 58382, Vancouver, B.C., V6P 6E4, Canada

Substantial gains in safety and economy in the clinical analytical laboratory are to be made in the preanalytic phase. Chemical and hematological analyses are largely performed by automated and dedicated machines. The distribution and interpretation of results can, and in larger labs often is done by various electronic information systems. However, relatively little innovative work has been done in specimen (e.g. blood) procurement, processing (centrifuging) and distribution (accessioning). These preanalytic tasks are the least technically developed. They require more time, expose employees to more hazards and result in more errors than any of the other stages of analysis. In recent times the fear of AIDS (acquired immune deficiency syndrome) has been partly responsible for a decline in the number of technologists training for medical laboratory service, a difficulty in hiring people for accessioning jobs and the imposition of severely restrictive and expensive workplace safety procedures in clinical laboratories. These problems beg for a safe, "intelligent" and automated substitute for the present manual methods.

Our goal is a system for fully automated blood processing from a patient's vein to delivery of sample aliquots at the in-tray of several specialized analysers. The system should permit staff avoidance of exposure to infectious agents, minimize mislabelling and processing time, and reduce the need for performance of dull, tedious jobs by highly skilled laboratory technologists.

A prototype robotic workcell was developed with system components which included a custom gripper to safely and reliably grasp and manipulate blood specimens contained in a variety of sample tubes; a Mitsubishi RM-501 robotic arm; a modified conventional benchtop lab centrifuge; a sample-weighing system for use with a dynamic centrifuge balancing algorithm; special test tube racks and an IBM personal computer for the operator interface which also controlled events and logged pertinent data for subsequent analysis.

This prototype was employed in the Division of Clinical Chemistry, Department of Pathology at the Vancouver General Hospital. More than 5000 blood samples were processed in an initial evaluation. Data was collected concerning safety, hardware and software reliability, the incidence and nature of errors encountered in sample handling, operator interfacing and other human factors and payback potential. A serious error rate of about 1%, optimum sample throughput of about 60 per hour, labour-saving payback of about 5 years and the need for considerable operator supervision were important limitations of the system. The major limitation to this approach was the slow and inefficient batch oriented mode of operation imposed by the centrifuge.

A useful solution to the preanalytic sample processing problem appeared to require a centrifuge which would be more adaptable to the robotic workstation. It would have provision for rapid serial processing and permit automatic sensing of sample quality, volume and identity. In addition more complete isolation of the sample would be required than is afforded by the most widely used collection and dispensing devices.

To meet these ends we have developed a proprietary axial centrifugation technology. A novel "Vacutainer-equivalent" plastic blood collection tube has also been developed to facilitate the use of this technology. It is robust and can be easily transported without need for special packaging to prevent breakage. It is also easily labelled or stamped with a barcode and can be incinerated. An integral rigid inner separator permits filtration of the specimen during isolation of the serum or plasma and it will keep the phases physically and chemically separate thereafter despite rough handling experienced during shipping. While a conventional centrifuge spins samples around an axis other than the major axis of the tube our processor spins a sample around its longitudinal axis. This feature facilitates important functions which are difficult or impossible with conventional methods e.g., monitoring of sample qualities such as lipemia, icterus and hemolysis during separation; barcoded sample-tracking; ejection of the serum during separation and simultaneous measurement of its volume; very short processing time (1-2 minutes) and optimization of serial sample processing. Most importantly this compact and mechanically simple device is well suited to robotic environments because the sample tube remains in a fixed position

during centrifugation and the rotor does not require balancing. The addition of a specialized disposable pipetting device permits manual, mechanized or hybrid sample processing with greatly reduced exposure of operators and others to the potentially hazardous specimen. Archival storage of separated specimens in the original collection tube is also facilitated by the pipetting device since no additional cap is require to prevent evaporation or danger of spillage.

A robotic workcell which employs this technology permits "hands off" processing of blood specimens from the time of their delivery to the lab in a completely enclosed and unbreakable collection container to the production of capped containers of serum aliquots ready to be placed on the sample trays of various analysers. The decision-making required for optimal sample splitting and response to sample characteristics as monitored by the workcell is supported by an "expert system"-like program running on a personal computer which also controls the robot and axial centrifuge. Throughput is sufficient to handle the workload of a large hospital or private clinical chemistry laboratory (about 180 specimens per hour) and payback on labour is estimated to be about 2.5 years. Initial clinical and field trials are being done in several major teaching hospitals.

In addition to obvious advantages to the clinical laboratory this proprietary technology promises major advantages in size, safety and adaptability to the needs of nearer-the-patient and doctor's office testing, portable and mobile laboratories and remote stations such as space.

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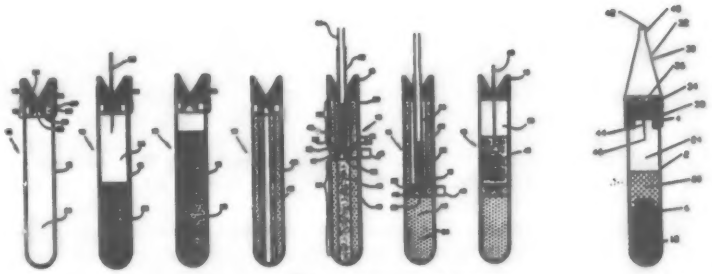
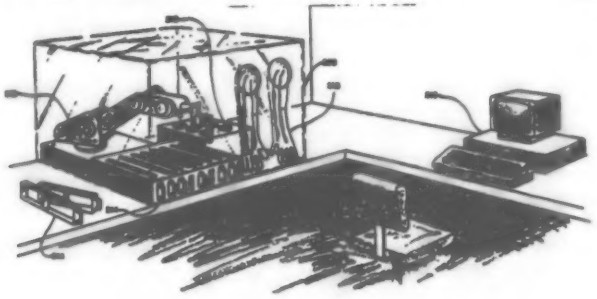


An evacuated blood collection tube which also permits separation, storage and aliquotting of the serum or plasma while remaining effectively sealed.



An enclosed robotic workcell which utilizes a battery of axial separation modules for processing the above device.

"MEDICINE: - THE POSSIBLE IMPACT OF ROBOTS ON CLINICAL AND LABORATORY PRACTICE"

Author: Dr. J.W. Buckler, MB ChB

Affiliation: Lecturer in Therapeutics, University of Nottingham
Clinician, City Hospital, Nottingham

Address: c/o 3 Clumber Crescent South, The Park, Nottingham, NG7 1EH, UK

Telephone: 0602 418161

Key Words: Robotics, Medical, Research, Hospital

Outline: The research consists of a carefully designed series of surveys of "normal" activities in a busy hospital. The hospital has routine service functions, but mainly has a teaching role. The paper aims to see how some of these activities could be advantageously modified by robots.

SUMMARY

Introduction:

Nottingham is a city of approximately 330,000 people but, as far as its hospitals are concerned, it has a drainage area of over 1,000,000. It houses one of the 3 teaching hospital units in the largest hospital area in the United Kingdom, i.e. the Trent region. The hospital structure is unique in that it was created as the first teaching hospital to be founded in this country during the present century. It has two principal hospitals: the Queen's Medical Centre and the City Hospital, Nottingham, which house almost every speciality. As with many hospitals they are troubled by cash and staffing shortages and, because of their teaching function these are especially acute. There must therefore be many ways in which robots could possibly help better to service the efficient functioning of the health care patients within the drainage area of Nottingham. The author has had the opportunity of serving on one of the DTI Committees, the Medical and Health Care Committee of the Advanced Robotics Initiative and obtained many ideas from this Committee and particularly from the Fulmer Research Institute. After many discussions a short list has been created by this Medical and Health Care Committee but this originated from a much larger list. It did seem that this would provide a list of headings whereby a clinician in active practice could assess the merits or demerits of such applications to Health Care. A clinician in active practice decided that over a 6 or possibly 8 week period, assessments would be made on the following units initially:-

A General Medical Consultant Referral Unit
A Specialised Cardiological Referral Unit and
pilot studies were completed.

Later, if the pilot studies were successful, it was decided that other studies would be carried out on a rehabilitation rheumatological unit and, within the laboratories of the particular hospital concerned, to determine whether or not there would be an advantage from robots in areas of contamination either due to viral diseases such as AIDS or hepatitis or from radiation. As an additional study it was decided to assess how the function of a major pharmaceutical research organisation within the city could be helped within its laboratories during animal research, by the use of appropriate robots.

Protocol Design:

This is sub-divided into the initial pilot study, then a study lasting 6 weeks involving two units and later a study of the Pathology Laboratory and of the Pharmaceutical Company's Laboratories previously mentioned. It was decided that activities in the hospital would be divided initially into two groups: those that could not conceivably be in any way helped by robots and those that possibly could. The researcher decided into which of the two groups the activity went, and, if in the latter group, assigned it to one of a large number of criteria. These were based on the results of series of brain-storming sessions held by Fulmer Research Institute, as a result of which, approximately 400 ideas for the application of Advanced Medical Robots were created. The author eliminated those from this list which were obviously impractical and also those which were duplications of others and was finally left with a list of N possible headings. When an activity was observed, it was categorised under one or of the other two groups and if in the second group under a number appropriate to that group. The only assessments made were those of the author and of a small group of other medical or medical auxiliary workers involved in the hospital. It was felt that a considerable degree of education would be needed to ask the opinion of other medical or para-medical workers as to whether or not a robot could be used in this activity situation. The pilot study was carried out over a period of two weeks on a busy general medical consultant referral unit and on a busy regional cardiological unit dealing with all types of heart disease including valvular disease, high blood pressure, congenital heart disease and myocardial infarction and angina including patients who had undergone or were about to undergo by- pass of their coronary arteries. Many of the patients with valvular disease had also elected to have artificial valve replacement. The initial pilot study of 2 weeks is being used to assess how to advance the design of this study into a much longer one and on to the other units previously mentioned. A copy of the list of criteria is available.

Results:

These relate to the pilot study and describe the assessment of N assessments of N activities. Preliminary analysis shows that a robot could have been used (on 39 occasions out of total number of activities of approximately 218). It is now intended that the study will proceed to look at work of the 2 units concerned over a concentrated 6 week period and later on at the Rehabilitation and the Pharmacological Research unit.

Discussion:

This promises to be an interesting and unusual study in that no such study has been done in this hospital region and particularly in the hospital concerned, combining, as it does, routine service functions with a teaching role. The pilot study suggests that appropriate robots would be of significant value within the hospital. As yet no assessment has been made on how these would affect the staffing or budgetary requirements of the departments concerned. It could well be that initial capital outlay did disadvantage such a project. Nevertheless it is anticipated that when some further assessment is made, particularly within the laboratory areas, that clear advantages can be shown.

Conclusions:

A pilot study of activities within a teaching/service hospital has suggested the need for further work as to whether or not a robot or a series of robots can show a clear advantage over normal staff functioning within the activities concerned in these hospital units.

Acknowledgements:

I am particularly grateful to the Fulmer Research Institute and to Dr. P. A. Finlay for allowing me to use as an outline in my protocol the headings which we created during the various brain-storming sessions.

DESIGN AND EVALUATION OF A LOW COST HYDRAULIC ROBOT SUITABLE FOR HAZARDOUS MEDICAL LABORATORY ANALYSES AND LIGHT DOMESTIC ASSISTANCE FOR THE DISABLED

L.A. GIFFORD
University of Manchester, Department of Pharmacy,
Manchester M13 9PL, U.K.

1. INTRODUCTION

Since the First International Symposium on Laboratory Robotics held in 1983, applications of the technology have increased dramatically both in number and in complexity. Work began in our laboratories in 1982 on the design and construction of a low cost robot suitable for use in pharmaceutical analysis (1). This paper describes the design and development of the robot, the integration into an analysis system for aflatoxins in milk and progress towards the construction of a food preparation station.

2. DESIGN AND EVALUATION OF THE HYDRAULIC ROBOT

A robotic device was required to perform the transfer of samples from one workstation to another. In the majority of cases the robot would only be required to perform pick and place operations but in some applications a reasonable degree of precision was required e.g. assembly of laboratory glassware. For such operations the control system required a commensurate degree of sophistication. The anthropomorphic design was selected as being the most appropriate for our needs. Low pressure linear hydraulic actuators (max 9 bar) were used to actuate the base, shoulder, elbow and hand. Drive to the wrist and gripper was provided by stepper motors. The gripper design was based on a two-finger clamping arrangement with the sample tubes held against a fixed V-shape support.

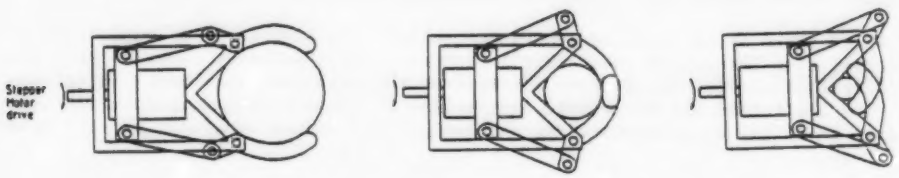


Figure 1 CAD schematic of robot gripper

Robot Control

The hydraulic actuators were controlled by solenoid valves. Due to problems with positional inaccuracy in the original design the hydraulic manifold was redesigned to provide both fast and slow operation of the hydraulic actuators. Speed was preset using variable restrictors in the hydraulic lines. Software stops were used to provide final positional accuracy (± 0.5mm). The on-board microprocessor was based on a 16-bit Intel 8088. Communication with the laboratory computer was via a standard RS232 serial interface which allowed the transfer of positional information. The arm was capable of moving in a cartesian co-ordinate system. Kinematic equations (2) were defined and linearised to give three equations relating to the changes in angles $\Delta\theta_1$, $\Delta\theta_2$, $\Delta\theta_3$ for small perturbations in vertical (ΔZ) and horizontal (ΔR) movement (fig. 2). This facility allowed the operator to move the gripper up-down/in-out in relation to a fixed point, thus making the approach and retract sequences much easier to perform.

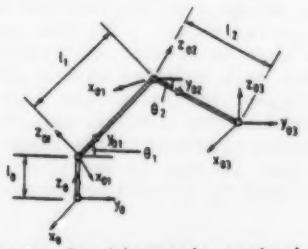


Figure 2 Definition of terms for kinematic analysis

3. AUTOMATED CHEMICAL ANALYSIS OF AFLATOXINS IN MILK

Aflatoxin M_1, is an extremely toxic and carcinogenic secondary metabolite produced by the mould of the genus Aspergillus. Regulations exist concerning levels of aflatoxins in food-stuffs and this work describes the development of unit laboratory operations for the robotic analysis of milk and related dairy products.

System Layout

Figure 3 shows a top view of the robotic system. The system comprised of four basic elements, (1) a

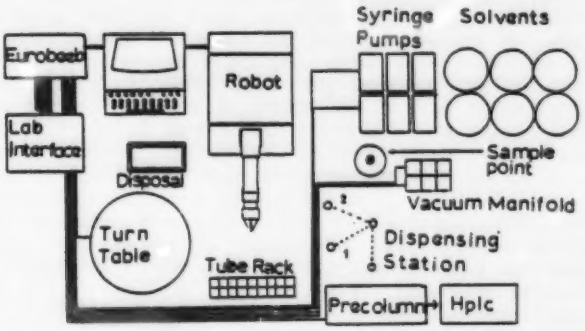


Figure 3 Top view of robotic system

six axis anthropomorphic hydraulic laboratory robot, (2) an IBM PC-XT micro computer controller, (3) a EuroBEEB microprocessor based real time controller and (4) a sample preparation station consisting of sample turntable, multisolvent dispensing facility, chromatographic separation station, test tube rack and automatic sample injection station. Other system components not directly accessed by the robot includes a precolumn sample separation and stream switching system, an hplc and a fluorimeter.

The IBM PC-XT acted as the overall system controller with bidirectional communication to the robot and to the real time laboratory instrument interface. Robot movement commands were generated by the IBM system controller as were operational commands to the real time instrument interface. The instrument interface controlled (1) the sample turntable, (2) the six syringe pumps, (3) the variable position dispensing head, (4) an electromechanical clamp, (5) a vacuum manifold, and the automatic hplc injection valves.

Microcomputer and real time laboratory interface

An IBM PC-XT (IBM Corporation, Boca-Raton, Florida, USA) was used as overall system controller and a EuroBEEB singleboard microprocessor controller (Control Universal Ltd., Cambridge, UK.) used for real time instrument control. Real time programming was achieved through use of the SPIDER software package (Paul Fray Ltd., Cambridge, UK.). Up to thirty two channels of opto-isolated I/O could be driven with the CUBE Delegate Driver card (Control Universal) which were defined in software as either inputs or outputs provided that they were not required simultaneously. Eight software clocks provided real time event scheduling. Connections to laboratory equipment were achieved through the use of two CUBE Delegate Industrial Interface cards (Control Universal). Each of the thirty two available channels had a status LED and two sockets which took 4mm standard plugs. If the channel was software defined as an input, a voltage between 5V and 30V was treated as a valid ON state; a valid OFF state was defined as OV i.e. an open circuit input. If the channel was defined as an output, a current sourcing load may have been connected, having a voltage between 5V and 30V, and the output could switch a maximum of 2A. The voltage drop across the Darlington transistor was limited to a maximum of 2.5V, catching diodes permitted inductive loads to be driven. All outputs had a common ground. In order to operate mains driven devices the 30V output from the Delegate driver was routed through a zero switching solid state relay which in turn activated a mains outlet socket. For the purposes of this application two 16 channel Delegate driver cards were employed to service two industrial interface cards. The industrial interface cards were housed in a 19 inch rack together with a seven socket mains distribution board fitted with Earth leakage protection (Olson Electronics Ltd., London, UK.). Analogue to Digital conversions and vice versa were performed by the CUBAN-12 interface (Control Universal Ltd.), which provided up to eight multiplexed ADC input channels in the range 0-10V unipolar and +/-5V or +/-10V bipolar. The interface also provided four latched output lines each having an independent adjustable amplifier which could give a maximum output of 10V and which could source up to 10mA.

Software

All communication in the system was through the IBM PC-XT. Communication with the EuroBeeb single board computer was facilitated with the EuroBeeb Terminal software package (Paul Fray Ltd.). Once loaded this then enabled the ROM based SPIDER software to be used to programme the real time sequence of control events. These sequences were stored in battery backed-up RAM and further communication between the main analysis programme on the IBM PC-XT and the EuroBeeb controller was via the serial interface.

Peripheral Devices

Custom designed peripheral devices were fabricated as follows: a rotary turntable for sample positioning, a variable position solvent delivery head, a motorised mechanical clamp and a vacuum switching manifold.

Sample Preparation and Analysis

Due to the low levels of aflatoxins required to be assayed (≈ 10^{-10} g/ml) a relatively large sample of milk had to be used (50ml). The aflatoxins are adsorbed onto a Bond Elut reverse phase cartridge and washed with seven different solvents prior to final elution and chromatographic analysis.

Results and Conclusions

Aqueous standard solutions and BCR Reference Milk Standards were analysed and the results compared with several manual methods. The results indicated that comparable precision and accuracy could be achieved and that the automated method was considerably more economical in terms of time as well as providing a much reduced safety hazard to workers. The flexibility achieved has led to the extension of the work into more difficult areas of sample preparation including the analysis of pesticides in vegetable products. The initial preparation required processing with a domestic food processor which has led us to consider the development of an automated food preparation station for use by the disabled.

4. FOOD PREPARATION STATION

Work is currently in progress towards the development of a food preparation station. A microwave oven, fridge and food processor will form the basic unit. Computer interfacing will be achieved using the hardware and software described in the laboratory analysis application. A suite of menus is envisaged which could be selected remotely by infra-red from a series of stored programmes. Ingredient selection and preparation would then be prepared by the robot.

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